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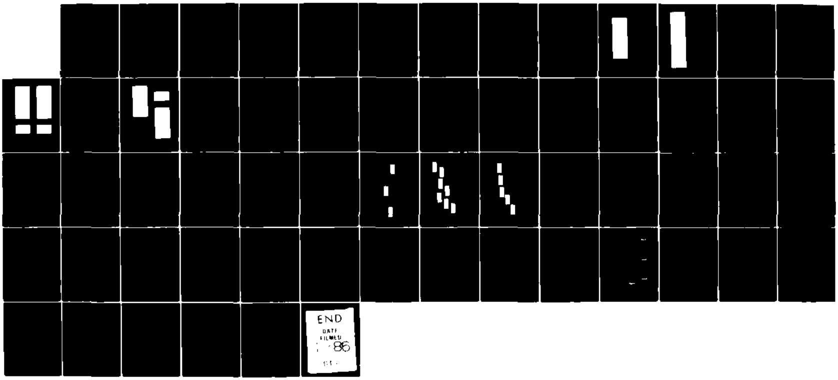

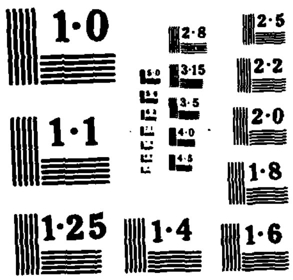
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MELBOURNE, VICTORIA

SYSTEMS REPORT 33

AN ANALYTICAL COMPARISON OF THREE VISUAL APPROACH SLOPE INDICATORS: VASIS, T-VASIS AND PAPI

by

JANE MILLAR

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SUMMARY

The three Visual Approach Slope Indicators (VASIs), [Red-White] VASIS, T-VASIS and PAPI, approved by the International Civil Aviation Organisation (ICAO) for use by turbojet aeroplanes, ~~are compared here.~~ The discussion is based upon published performance data including approach path measurements and pilot opinion, ergonomics and the ability to fulfil operational requirements.

It is concluded from flight trial data and operational experience that T-VASIS is a more precise and sensitive a[illegible] than Red-White VASIS which has several deficiencies known for many years. The current policy of not using Red-White VASIS for routine operations in Australia is supported by the conclusions of this report.

It is predicted that PAPI also will be less satisfactory than T-VASIS. This prediction is based mainly on ergonomic principles. Performance data about PAPI is limited and consists mainly of relatively uninformative pilot acceptance surveys. Because insufficient objective parameters describing trajectories of aircraft from the intended user-population have been published, most of the claims for PAPI superiority remain unsubstantiated.

Accordingly, it is recommended that PAPI be evaluated using objective measures in a controlled experimental environment with transport aircraft. Further, because of its ergonomic deficiencies, PAPI should not be installed in Australia for routine operational use by turbojet aeroplanes at this stage.

POSTAL ADDRESS: Director, Aeronautical Research Laboratories,
Box 4331, G.P.O., Melbourne, Victoria, 3001. Australia

CONTENTS

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1. INTRODUCTION

Landing an aircraft, particularly in an environment containing limited visual cues, can be an extremely demanding task for a pilot. The difficulties involved are reflected in the frequency of accidents in the approach and landing phases. For instance, during the years 1961 to 1972, 55% of all civil aviation accidents in the USA occurred in these phases (NTSB 1973). Accidents are more likely during the night than the day, by a factor of 2·5 (NTSB 1973). Although many accidents occur in reduced visibility conditions (NTSB 1973), a surprisingly high frequency of accidents happen in clear weather at night (Kraft 1969; Hasbrook 1975).

Often landing accidents are attributed to "pilot error"—a category which implies a multitude of interacting causes and reasons (see Hartman and Cantrell 1968). Although the exact causes of human factor-related accidents subsumed under the "pilot error" heading are difficult to determine during subsequent investigations (Zeller 1970), pilot opinion surveys (e.g. Lane and Cumming 1959) and anecdotal reports from pilots indicate that perception of so-called "visual illusions" can play a major role (see Pitts 1967; Iwataki 1973; Armstrong, Bertone and Kahn 1972; Hasbrook 1975). Experimental evidence suggests that most commonly pilots tend to overestimate their approach angle (Mertens 1979) and hence fly too low. Consequently, the aircraft may either land short of the runway or hit obstacles that would have been cleared had a proper approach slope been maintained. Even when a pilot is aware of and may expect these illusions, the approach path may sometimes look normal when it is not, and this perception compels the pilot to persist in reacting incorrectly, so causing the aircraft to depart from an acceptable trajectory.

Between twenty and thirty years ago several possible solutions for improving landing success were suggested. Some persons (e.g. Sparke 1958) thought that when the relevant technology had been developed the pilot could be removed altogether from the aircraft control loop and be replaced by more accurate and therefore safer automated mechanical and electronic devices. Automatic landing equipment guided by the ILS beam was then, and still is, commonly installed in aircraft. However, these devices are not as successful as one may have hoped. Many of them used currently are not always reliable (especially in strong winds) nor accurate enough, despite the technological advances during the ensuing years, and more sophisticated devices like *Autoland* have not proved cost-effective in many operational situations.

Technical and economic factors are not the only difficulties associated with automated landings. Another difficulty derives from the underlying premise that the pilot can be totally replaced by automated control systems; this is an idea that has received a good deal of attention in the human factors literature (see Wiener and Curry 1980). Even if safe landing could be achieved by automated means at a very high success rate, the pilot would still be required in a supervisory role and may have to intervene should equipment fail. During an automatic landing, the information about the flight trajectory needs to be exceptionally clear and unambiguous (Lane and Cumming 1956) for the pilot to decide quickly about any remedial action. Hence, the pilot's perception and interpretation of the visual world remains a critical feature during approach and landing.

Other solutions to better landings rely on assisting the pilot to monitor visually his aircraft trajectory by referring to an airborne or a ground-based aid (Lane and Cumming 1956). Ground-referenced airborne displays, which integrate data from flight instruments and generate flight-director type information about the approach, have been developed and are now included in the generic class of head-up displays (HUDs) (Naish 1979). Similar concepts were given special emphasis by Lane and Cumming (1956) when they investigated landing aids. During the late 1950s ARL and the Government Aircraft Factory devised prototype HUDs for landing (e.g. Henshall 1958), but technical difficulties retarded their development. Since then a great deal of effort has been directed into HUDs developed for other phases of flight and these are now in service.

Interest in ground-referenced approach HUDs is high, but they are still under development elsewhere (Naish 1979).

Ground-based visual approach aids, designed to assist pilots' visual judgements, have also been installed at many of the major and secondary airports throughout the world. One example is pre-threshold approach lighting which has been developed (especially by Calvert (1949, 1955, 1958) into a "mat" of lights providing the pilot with extra geometry from which to judge an appropriate approach slope using perspective cues. Additional geometry is also sometimes given by special markings painted on the runway (e.g. diamonds, see Swaroop and Ashworth (1978)). Further specialised lighting systems have also been installed adjacent to the runways near the aiming point. These aids provide explicit signals about the approach angle, principally, and are known as Visual Approach Slope Indicators (VASIs). Many VASI signalling systems have been devised for landing various aircraft types both for civilian and military applications.

This current report is concerned with the VASIs that have been approved or are under consideration for approval by the International Civil Aviation Organisation (ICAO). Installation of a VASI is recommended by ICAO at runways used by aeroplanes engaged in international air services, particularly turbojet aeroplanes or other aeroplanes with similar approach guidance requirements (see ICAO, Annex 14, Section 5.3.6.1).

At the time of writing, the ICAO standards approved two types of VASIs for use by these aircraft (ICAO, Annex 14). The first, approved in 1961, was VASIS (called Red-White VASIS in this report) which was developed in Britain by Calvert and Sparke at the Royal Aircraft Establishment (RAE) (see Sparke 1958). The second, accepted in 1962, was T-VASIS (see Baxter and Lane 1960) developed in Australia jointly by Cumming and Baxter of the Aeronautical Research Laboratories (ARL) and Lane, Leevers and Fraser at the Department of Civil Aviation (DCA, later the Department of Transport, DoT, and now the Department of Aviation, DoA).

More recently, a new VASI, called the Precision Approach Path Indicator (or PAPI for short) has been developed at RAE by Smith and Johnson. They suggested that PAPI could be suitable as a replacement for all current glideslope indicators and could be adopted as the standard VASI (Smith and Johnson 1976). Following this suggestion, Brown, representing the United Kingdom Civil Aviation Authority (CAA), recommended to the ICAO Visual Aids Panel (VAP) that PAPI be included in the ICAO standards as an alternative to and eventually as a replacement for Red-White VASIS (VAP 1978).

The Visual Aids Panel (VAP 1978) agreed to consider Brown's proposal. Subsequently, a recommendation to accept PAPI was made to the ICAO meeting of the Aerodromes, Air Routes and Ground Aids Division in April–May 1981, based upon the findings of a subcommittee —the PAPI Working Group—which was authorised to evaluate PAPI and report to the ninth VAP meeting. A number of member countries including Belgium, Canada, France, Niger, UK and USA (VAP 1980) agreed to participate in the working group and to undertake an evaluation of PAPI. Australia was invited to join the Working Group at a later date and the USSR also indicated interest in the evaluation.

The VAP directions to the PAPI Working Group excluded a comparison of PAPI with both VASIs approved by ICAO, but instead specific attention was to be devoted to a comparison with Red-White VASIS. T-VASIS was not to be considered even though it is demonstrably a superior aid to Red-White VASIS; a fact also noted by Paries (1979). Notwithstanding this decision, a comparison between T-VASIS and PAPI would be entirely consistent with ICAO principles of international standardisation; proliferation of different types of VASIs designed for the same aircraft type but working from different principles is most undesirable from an ergonomic viewpoint.

An attempt has been made here to overcome the omission of T-VASIS by comparing PAPI with both T-VASIS and Red-White VASIS. Because the original concept of PAPI was intended for Short Take Off and Landing (STOL) aircraft (CAA 1978), and it has since been adapted for fixed-wing heavy transport use, the suitability of PAPI for international aviation operations is carefully considered below. Special emphasis is placed on aspects of ergonomics known to be relevant to successful VASI design for fixed-wing transport aircraft. Technical details about the construction of PAPI boxes are, in the main, ignored in this paper except where they impinge on ergonomic considerations.

It was originally intended that a paper such as this be made available for consideration

by the ninth VAP meeting as part of the Australian contribution to the debate about PAPI. However, the paucity of information published prior to the meeting precluded a sufficiently complete analysis by that time. Instead, the major review has been extended and covers articles which appeared to December 1981. A draft summary of our findings and conclusions about PAPI up to November 1980 was presented to ICAO (Arnold 1981) and an edited version has been published in the official ARL series (Millar 1982).

2. DESCRIPTION OF THE THREE VASIs

2.1 Red-White VASIS

Red-White VASIS consists of rows of three boxes aligned perpendicular to the runway edge and so forming "wing" bars. The two sets of wing bars used in the standard version are separated by 210 m and sited symmetrically upwind and downwind of the nominal aiming point (see Fig. 1). Each box projects a beam of white light in its upper segment and red in the lower. A region of pink light, termed the transition zone, occurs between the white and red segments and results from mixing of the two colours. This region should not subtend more than 15′ of arc according to ICAO specifications in Annex 14, but often does (Gates and Paprocki 1972*a*; Smith and Johnson 1973, 1976).

The downwind boxes are usually aligned (depending on the boxes used to generate the signals) so that the white light appears at approach angles above 2·75°; the white light appears at angles above 3·25° in the upwind boxes. This arrangement therefore provides three sets of signals. An approach within the "on-glideslope" channel is signalled by red upwind and white downwind wing bars. Deviations below the acceptable channel result in all red signals; for deviations above, the wingbars turn white (see Fig. 2*a*).

There are several versions of Red-White VASIS for use in a variety of circumstances. The principal difference lies in the number of light boxes installed. The alternatives have either three, two or one box(es) in each wing bar on one or both sides of the runway and the code of the runway specified by ICAO determines which type should be installed. Seven different configurations are now incorporated into the ICAO standards (Annex 14), although at times there have been up to ten.

When wide-bodied aircraft entered commercial service (e.g. B747, DC-10), Red-White VASIS was modified from its original two bar form by the addition of a third set of wing bars upwind (a three bar form) thus defining two approach channels; one with a nominal aiming point further past the threshold than the other. Figure 1 also shows the cut-off angles and siting positions of 3-BAR Red-White VASIS.

Four signals are provided by 3-BAR Red-White VASIS because the pilot may select an approach channel formed either between the upwind and middle wing bars or the middle and downwind wing bars. A pilot of a B747, for instance, should fly the approach within the channel formed by the upwind and middle wing bars. When "on-glideslope" this pilot will see two white and one red (the upwind bar) wing bars on each side of the runway as shown in Figure 2*b*.

2.2 T-VASIS

The full T-VASIS consists of twenty boxes, with one group of ten on each side of the runway. Four of each ten boxes serve as wing bars and are placed in pairs, orthogonal to the runway edge. These are visible from approach angles between 0° and 15°. The remaining six units from each group (called "leg" boxes), which are visible according to elevation, are placed longitudinally down the runway side. Figure 3 shows the layout and cut-off angles of T-VASIS (see Baxter and Lane 1960; DoT 1974; or ICAO Annex 14 for a complete description). It is usual for the full T-VASIS using all twenty boxes to be installed, but an abbreviated system (AT-VASIS) where one group of ten boxes is installed on one side of the runway only has been endorsed by ICAO.

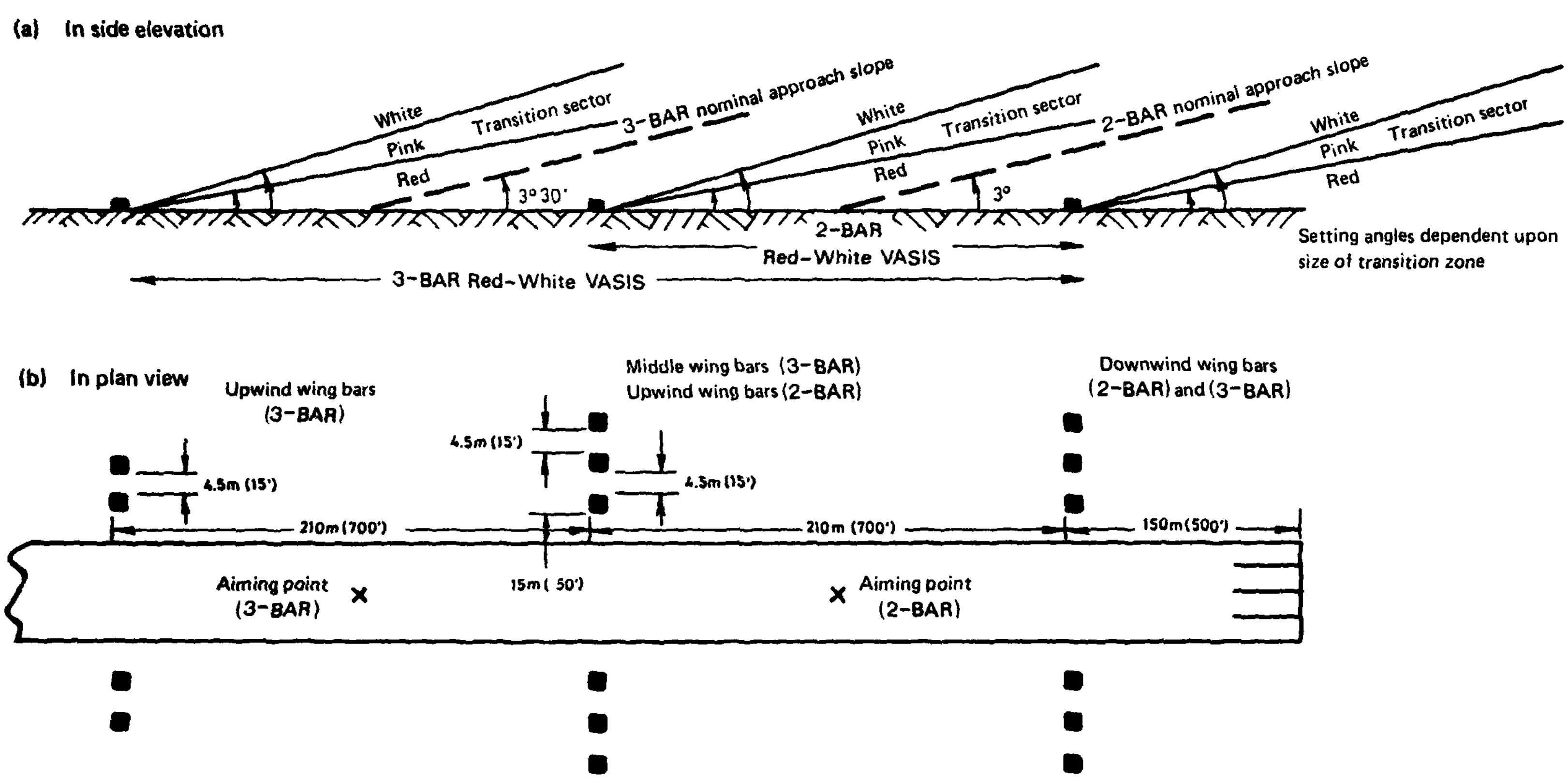
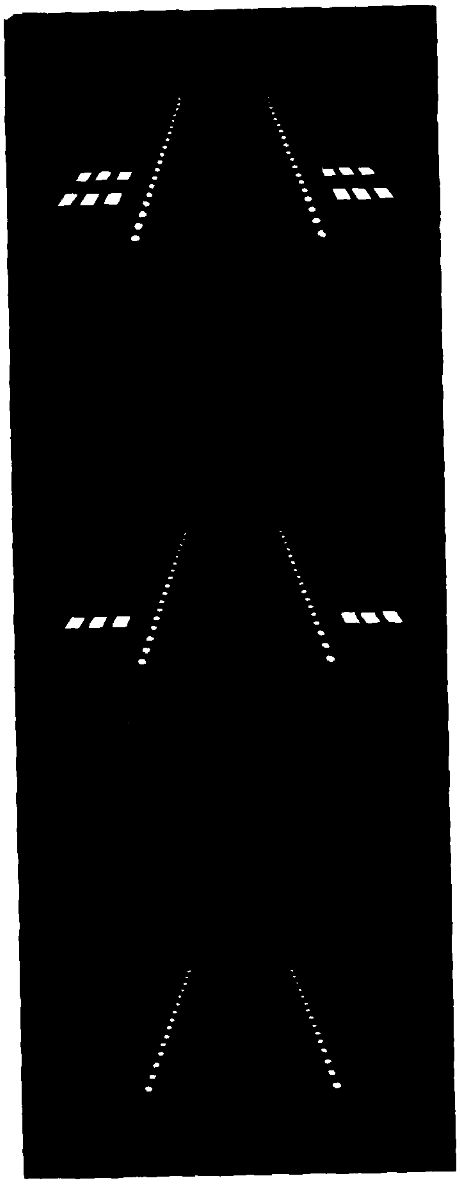


FIG.1 RED-WHITE VASIS SCHEMATIC LAYOUT (not to scale)



Above approach slope

On correct approach slope

Below approach slope

FIG. 2(a) 2-BAR RED-WHITE VASIS SIGNALS AS SEEN BY THE PILOT OF AN AIRCRAFT ON APPROACH

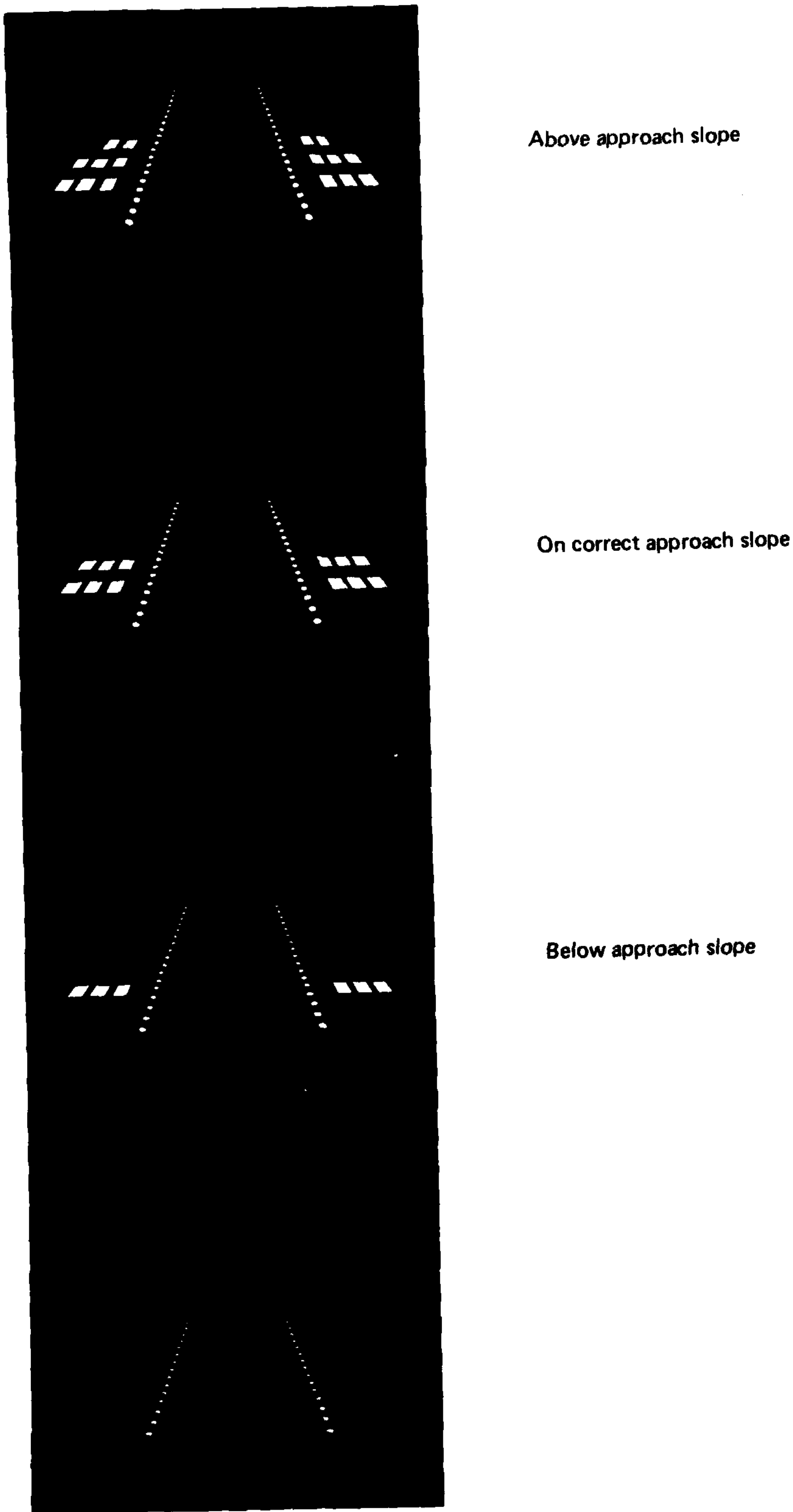


FIG. 2(b) 3-BAR RED-WHITE VASIS SIGNALS AS SEEN BY A PILOT ON APPROACH USING THE UPWIND CHANNEL OF THE SYSTEM

T-VASIS provides the pilot with information about his *deviation from glideslope* and directs the appropriate response (see Figure 4). The pilot descending to land will see:

(*a*) when above the approach corridor a "fly down" signal with the wing bars white and one, two or three white leg lights forming an inverted "T" shape.;

(*b*) when within the approach corridor, only the wing bars;

(*c*) when below the approach corridor the "fly up" signal with the wing bars and one, two or three white leg lights forming the shape of an upright "T".

T-VASIS thus provides seven major white *glidepath indications*. Extra warning of an extremely low approach is provided by a change in colour of the upright "T" leg boxes and wing bars. The boxes turn red progressively, but over such a narrow range of angles that the red signals are seen almost simultaneously during undershoots.

2.3 PAPI

PAPI (the Precision Approach Path Indicator) was developed at RAE by Smith and Johnson (1976) primarily as a tactical landing aid for STOL military aircraft (CAA 1978). In their 1976 paper, Smith and Johnson reported an adaptation of the PAPI STOL design for major airports. Consequently, there exists a number of alternative arrangements of PAPI depending upon the intended use of the system.

The simplest PAPI configuration suggested for commercial operations consists of a basic group of four boxes on the ground placed in a line orthogonal to the runway edge, preferably opposite the nominal aiming point (see Fig. 5). It was not clear from the earlier descriptions in ICAO minutes whether it was intended that PAPI be installed on both sides of the runway. However, a one-sided system is now standard (VAP 1980, Appendix F; AGA 1981). Like Red-White VASIS, each box emits an upper segment of white light with the lower segment red. The pink transition zone between the segments is very small and was designed to be 2′ to 4′ of arc, according to Smith and Johnson (1976). (This value of 2′ to 4′ of arc apparently refers to measurements made at the optical axis; the transition zone widens when observed from off-axis and a restriction of 10′ in the width at 10° has been suggested by Hald (1980).) The British have since recommended 5′ at 15° from the optical centre (AGA 1981, Appendix A).)

Each PAPI box is aligned to change colour at a different angle to its neighbours. Typically, these colour changes are arranged with increments of 20 minutes. *Five signals are defined* (see Fig. 6). The "on-glideslope" signal displays the two lights furthermost from the runway as white and the two lights innermost as red. Descents from the nominal approach path result in firstly the innermost of the two white lights altering to red as the transition zone of the box is crossed, resulting in one white and three red visible lights; a further height decrease results in four red lights appearing after the transition zone of the last box has been traversed. Correspondingly, increases in elevation from the glideslope are signalled to the pilot by the red lights in his view being successively replaced by white lights (see Fig. 6).

The size of the sectors in PAPI can be altered readily to change the precision of the VASI. PAPI is therefore a generic name and does not refer to any one configuration. For consistency in this paper, when necessary, the size of the segments will be indicated in brackets; e.g. PAPI (20′, 20′, 20′) defines the standard configuration mentioned above.

Another arrangement of PAPI, using two bars on each side of the runway rather than one, was suggested by Smith and Johnson (1976) as suitable for wide-bodied aircraft. A 2-BAR PAPI installation has not proved successful in operational trials (Brown 1980) and is discussed in Appendix A. A modified one bar system has been suggested as a suitable replacement for the two bar form (VAP 1980).

3. EVALUATION OF PERFORMANCE CHARACTERISTICS AND PILOT OPINION

3.1 Red-White VASIS and T-VASIS Performance During Flight Trials

Red-White VASIS has been evaluated on many different occasions. The first evaluations were undertaken to compare the performance with that of the Precision Visual Glidepath (PVG)

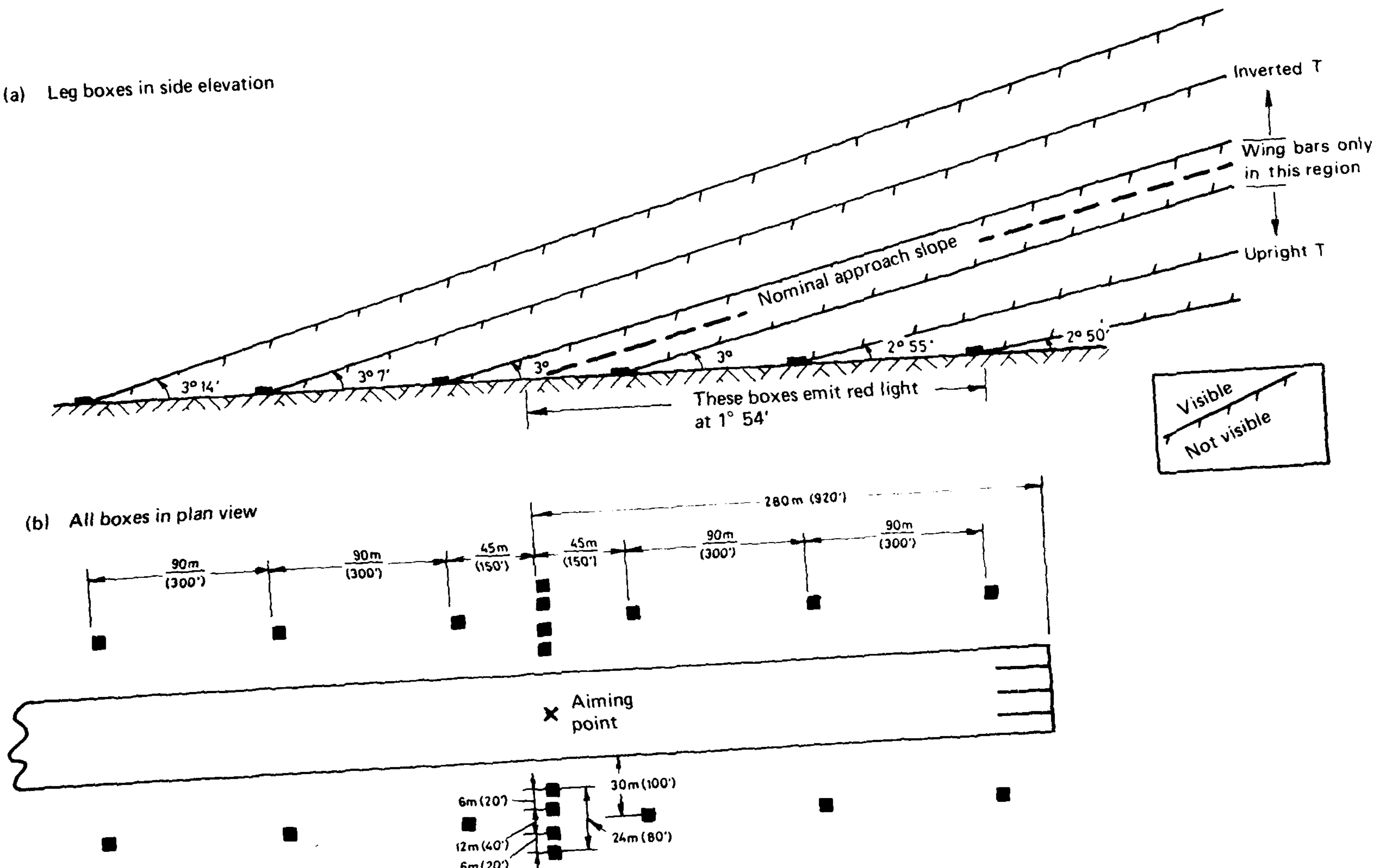
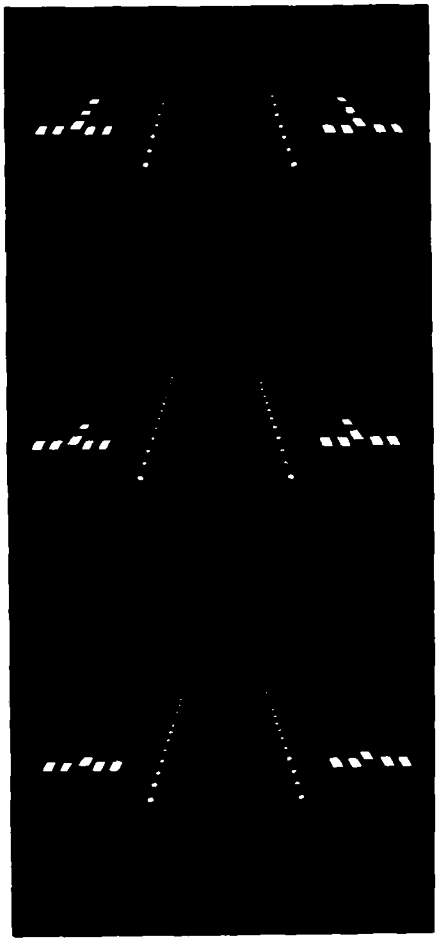
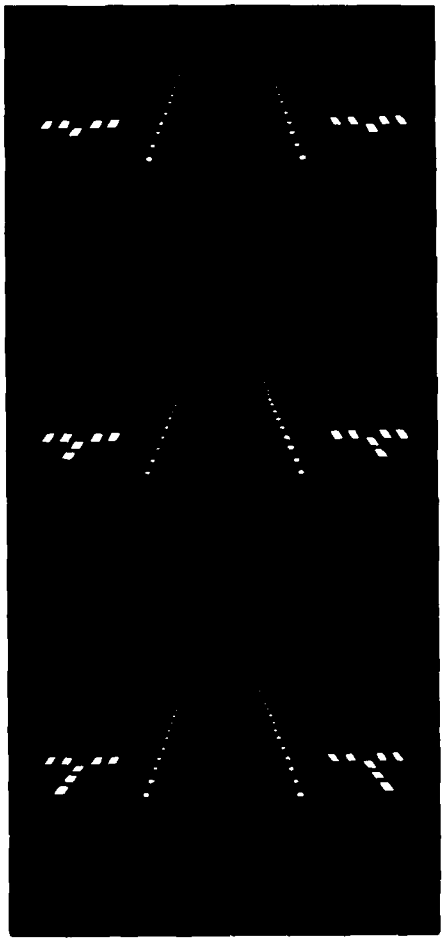


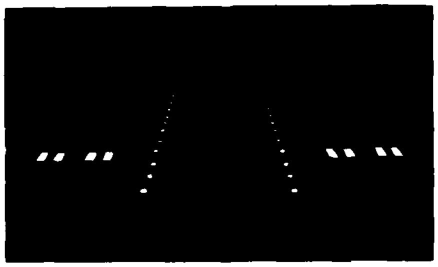
FIG. 3 T-VASIS SCHEMATIC LAYOUT (not to scale)



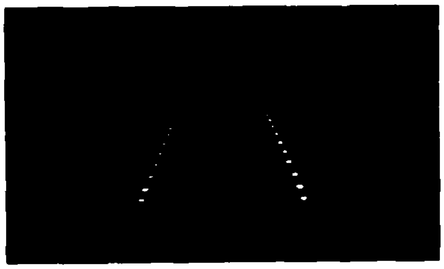
Above approach slope
'FLY DOWN'



Below approach slope
'FLY UP'



On correct approach slope



Gross under shoot signal
'DANGER'

FIG. 4 T-VASIS SIGNALS AS SEEN BY THE PILOT OF AN AIRCRAFT ON APPROACH

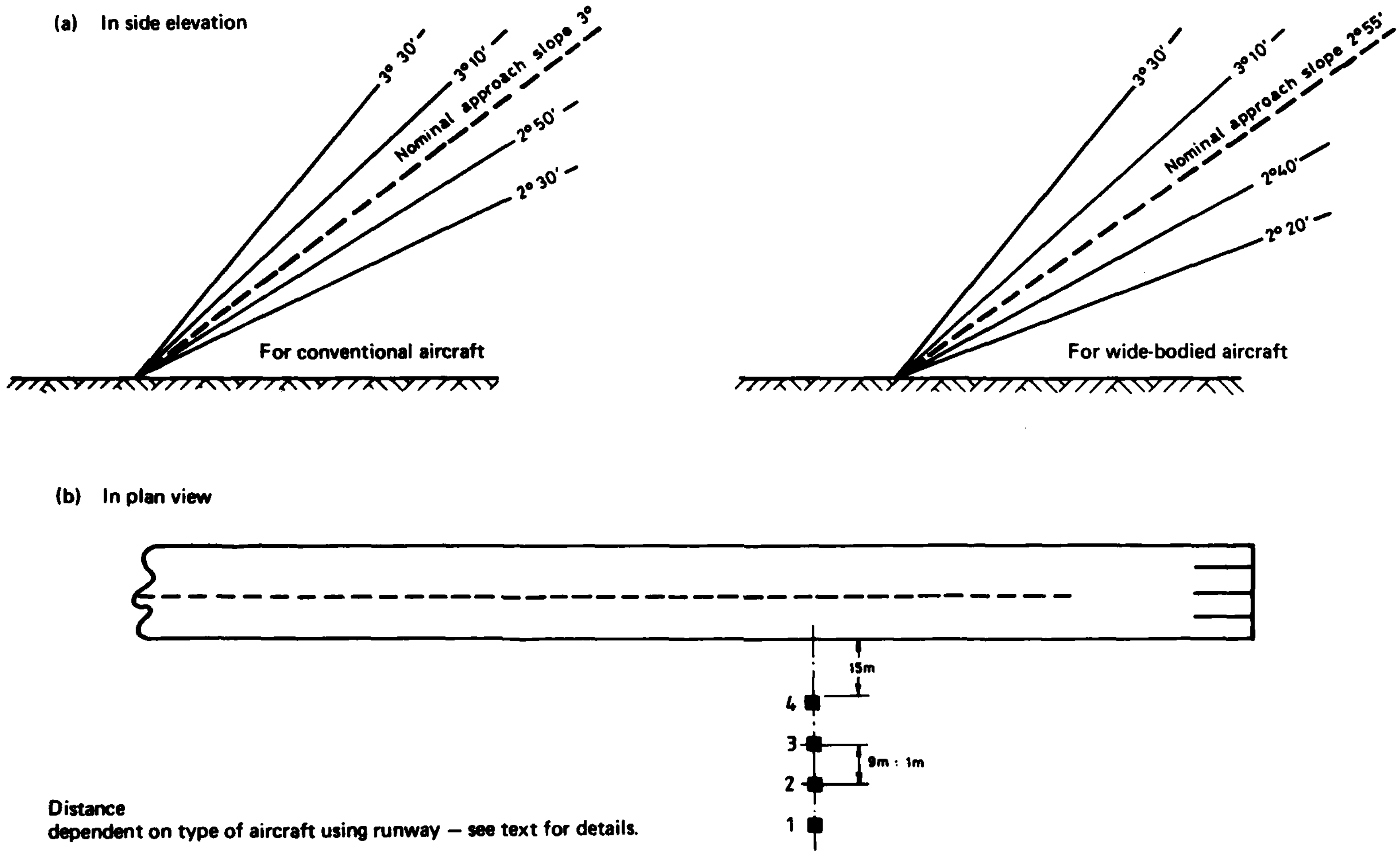
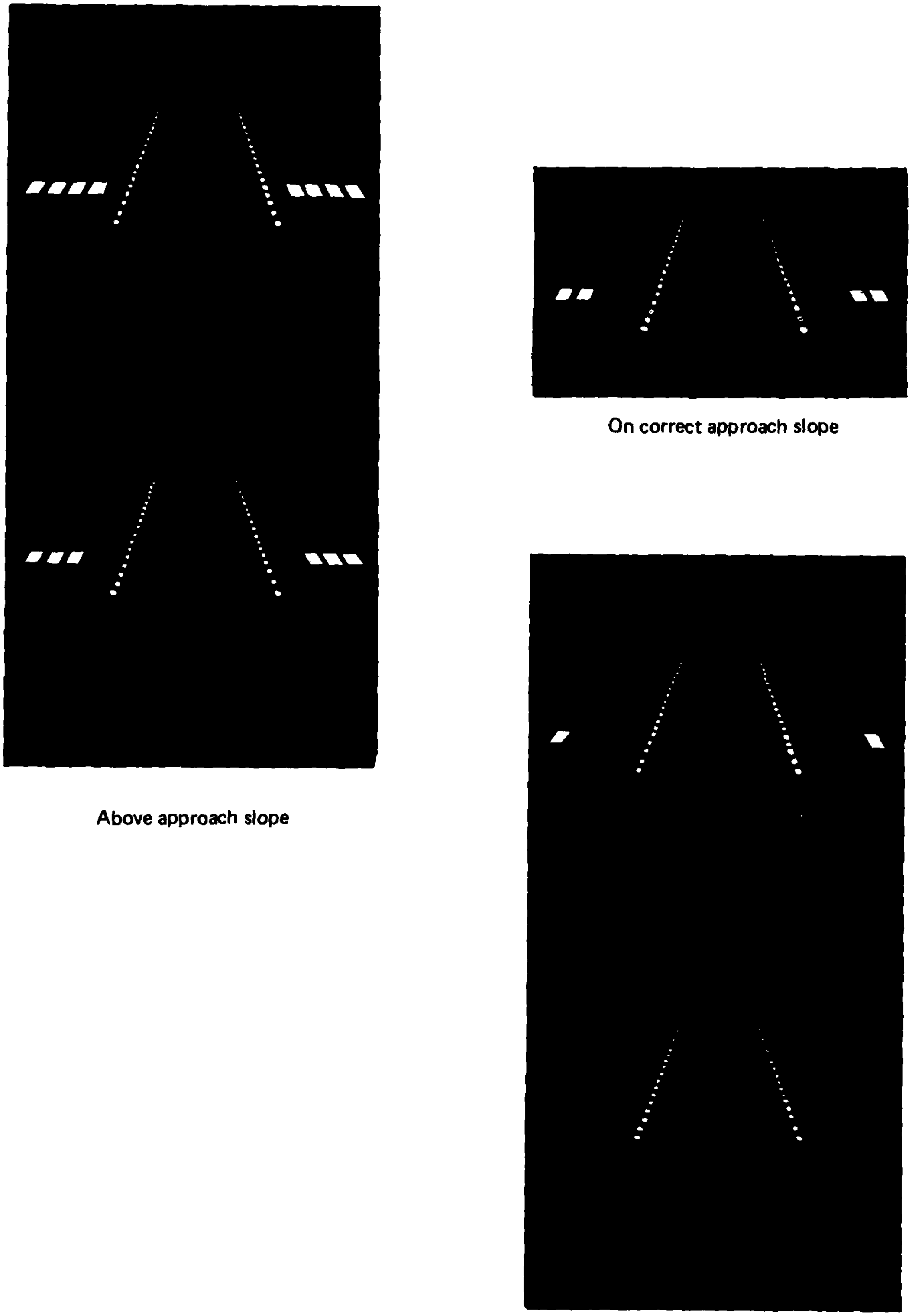


FIG. 5 PAPI SCHEMATIC LAYOUT (not to scale)



Above approach slope

On correct approach slope

Below approach slope

FIG. 6 PAPI SIGNALS AS SEEN BY THE PILOT OF AN AIRCRAFT ON APPROACH

(a VASI developed in Australia using the guidance principle of the mirror deck landing system (Cumming and Lane 1957*a*) which has been described by Lean (1954) amongst others). Measurement of pilot flight trial performance using objective parameters could not distinguish between Red-White VASIS and the PVG (Day and Baxter 1959; Morrall 1960; Baxter, Cumming, Day and Lane 1960). Pilot opinion elicited from twelve pilots inexperienced with VASIs did tend to favour the PVG in one experiment (Day and Baxter 1959), but the majority of pilots in another experiment preferred Red-White VASIS (FAA 1960). Statistical significance between preferences was not obtained in either experiment (Baxter, Cumming, Day and Lane 1960).

Dissatisfaction with both these aids led to the development of T-VASIS (Baxter and Lane 1960). T-VASIS was specifically designed to try to overcome certain disadvantages of Red-White VASIS (mainly the colour coding and the low precision guidance) and of the PVG (the vulnerability to poor atmospheric conditions and the inability to provide adequate information over the whole distance required). Since then Red-White VASIS has been mainly evaluated either alone or in comparison with T-VASIS.

The results from the early comparisons clearly demonstrated that T-VASIS was the more precise and sensitive aid. Objective measures of performance such as root mean square (RMS) deviation in height about the nominal glideslope (Baxter, Cumming, Day and Lane 1960; Hyman 1963) and threshold crossing height (or height over threshold, HOT; Cumming 1962) showed strong statistical differences in favour of T-VASIS. Hyman (1963) reported that he could not differentiate between the two aids using HOT measures although he apparently did not base this report on a statistical comparison. In fact, his data showed that the range of HOT for Red-White VASIS had markedly lower and higher scores than for T-VASIS, which suggests that statistical differences may have been found if the appropriate tests had been applied.

Subjective measures concur with the performance differences. When opinions were sampled from representative groups of military and/or commercial pilots, carefully selected to avoid bias from previous exposure or knowledge, T-VASIS was preferred to Red-White VASIS on most items in the extensive lists of parameters sampled in each survey (Alexander 1962; Baxter, Cumming, Day and Lane 1960; Hyman 1963).

Some of the pilots in the first trials of T-VASIS for the US Air Force undertaken by Hyman (1963) commented unfavourably about a few minor features, including the separate flashing red lights which signalled a gross undershoot in the prototype T-VASIS equipment (called TEE) which was used. Because TEE equipment was tested, Hyman (1963) was unable to recommend that T-VASIS take precedence over Red-White VASIS until his suggestions were implemented. Subsequently the separate units which flashed the signal were deleted from the design and a steady red signal was incorporated into all the T-VASIS wing bar and "fly-up" boxes to warn the pilot when he was approaching at an unacceptably low angle. Adjustment was also made to the lateral spread of the emitted light. This modified T-VASIS design was the one accepted by ICAO.

The USA National Aviation Facilities Experimental Center (NAFEC) re-evaluated T-VASIS (using AT-VASIS) in the middle 1970s and, on the basis of pilot opinion, a preliminary report concluded that T-VASIS was "a most desirable substitute" for 3-BAR Red-White VASIS in an experiment conducted in Atlantic City (Jones 1977). However, the pilots were not required to use Red-White VASIS during the experiment and so relied on their memory to make the comparison. Operational trials of AT-VASIS were also conducted by NAFEC at Miami International Airport where airline pilots and general avaition pilots were invited to complete questionnaires. According to a brief report, about 80% of airline pilots preferred T-VASIS and it was recommended that "the FAA should consider substitution of the T-VASIS for the three-bar VASI" (FAA 1978).

More recently a simulator experiment was conducted to compare the performance of pilots when guided by T-VASIS, 3-BAR Red-White VASIS, 2-BAR PAPI and 2-BAR Red-White VASIS (Lewis and Mertens 1979*a*, 1979*b*). The results showed superior tracking accuracy using T-VASIS with decreased performance for the other VASIs in the order listed above. (This experiment is discussed more fully in Appendix A.)

Simplified Red-White VASIS (SAVASI) installations for use by lighter aircraft have also been tested several times. Two comparisons assessed the effectiveness of SAVASI as a training aid for learner pilots by using a control experimental condition of "no aid". Conflicting results

were reported. Crook (1970) found the aid to be useful in limiting the amount of practice required to execute a good landing, although Smit (1975) found the aid to be of no use. SAVASI has been recommended for use at USA secondary airports following other evaluations. Gates and Paprocki (1972*b*) reported that in their comparison SAVASI proved superior to VAPI (a tri-coloured aid). Dosch (1979) compared a large variety of low cost systems and agreed that SAVASI was superior to VAPI for some applications. However, for other applications Dosch (1979) preferred certain derivatives of the PVG (e.g. POMOLA).

The performance of pilots using Red-White VASIS was also assessed by Smith and Johnson (1973). They reported that adequate threshold clearance [or HOT] was obtained during tests where B707 aircraft were flown manually in daylight approaches. However, the authors doubted that the clearance obtained was a direct consequence of the VASI placement; rather the scatter of touchdown points was a more important parameter. Smith and Johnson (1973, 1976) go on to say that when pilots see the "too low" Red-White VASIS signal they commence their flare earlier to achieve adequate clearance at the expense of touchdown accuracy. This opinion was apparently formed without the assistance of a statistical analysis and in the absence of a comparison or control experimental condition. Moreover, the view that HOT achieved with Red-White VASIS is adequate conflicts with the results of Cumming (1962) discussed below.

Shortcomings in the guidance characteristics of Red-White VASIS were also mentioned by Smith and Johnson in 1976. They reported that the tracking performance of pilots was unsatisfactory mainly because an oscillatory flight path was induced which could result in the aircraft landing short (Smith and Johnson 1976). Data was not provided nor was a description of the experimental conditions under which these results occurred, but similar findings are evident in some of the trajectories obtained in the earlier Australian work.

Performance of Red-White VASIS in the field has also been compared with PAPI on two occasions. The results from these evaluations, one by Smith and Johnson (1976) and the other by Paries (1979), will be discussed more fully further on. Neither reported particularly favourable findings about Red-White VASIS.

3.2 Operational Trials of Red-White VASIS and T-VASIS

Most of the field trials mentioned above which tested Red-White VASIS or T-VASIS, or both, were experimental trials designed to discover any differences between the two aids. One study by Cumming (1962) investigated whether these differences were of practical significance in a fully operational environment.

In this study the two aids were installed on the same sides of a runway at Sydney Airport used for international operations. (At that time DC-8s and B707s were flown internationally, and landed during the day only.) On successive occasions one or other of the aids or neither aid was activated, and the proficiency of approach was measured for every aircraft using the runway. Ostensibly, the pilots thought that the reason for the procedure was to obtain their opinions about the operating VASI, and so their approach performances were unlikely to have been biased by the knowledge that their flying was being monitored (Cumming 1962). Cumming adopted this procedure to avoid complicating the results by any possible motivation to excel which may occur in experimental trials.

When Cumming compared the distribution of either HOT of pilot eye or HOT of the aircraft wheels (after normalisation by a logarithmic transform) he found that approaches with T-VASIS were more consistent than those made with either Red-White VASIS or no aid. It was possible for Cumming to calculate from these distributions the probability of touchdown prior to or at the threshold. This probability was estimated to be almost three orders of magnitude larger for Red-White VASIS when compared with T-VASIS values. Red-White VASIS did not reduce the statistical probability of an undershoot accident from that of an unaided approach; T-VASIS significantly reduced this probability (Cumming 1962).

3.3 Accident Records

Another source of determining the effectiveness of a VASI after its introduction into the operational environment is from accident records. However, because these records usually do

not fully document human factor-related accidents (for a variety of reasons—see Zeller 1970), it is difficult to implicate inadequacies in VASI design which may have contributed to a "pilot error" accident. In Australia however, undershoots are rare and it is possible to keep a careful watch on whether accidents occur on runways where T-VASIS is installed. As far as it is known to the author, only two such accidents have occurred where T-VASIS was operating. In one, the foreign flight crew chose not to use the aid (DCA 1972); in the other the pilot executed a short circling approach in poor meteorological conditions (DoT 1976). In neither circumstance did the accident investigators consider T-VASIS to be a causal factor.

It is difficult for an Australia-based author to ascertain the frequency of accidents which have occurred when Red-White VASIS was in use because the aid is mainly installed on runways in America and Europe and the corresponding detailed records are not readily available here. At least one accident has been recorded elsewhere when Red-White VASIS was in use (CAB 1966) and a possible reason will be discussed further on (Section 4.5.3).

3.4 PAPI

As mentioned in the Introduction of this report several member countries of ICAO expressed an interest in conducting evaluations of PAPI. The results which were published by December 1981 are reviewed in the following sections.

3.4.1 Pilot opinion

By far the most popular method which has been used to assess PAPI is by surveying pilot opinion. Surveys have been undertaken in several countries including Belgium, Canada, Denmark and the United States of America as well as the United Kingdom. However, many of the reports are anecdotal and make vague generalised statements, viz.:

(i) "In *all* cases pilots have reported that the system is easy to fly and gives precise information as to the aircraft's position." (Smith and Johnson, 1976);

(ii) ". . . *all* pilots expressed favourable opinion about the system." (Hald, 1980) (emphasis by present author).

In addition, some reports were exceedingly brief and did not describe the methods used when collecting the information (e.g. VAP 1980, para 1.4.5 and Appendix B). While these statements and reports may truly reflect the opinions of the participating pilots they cannot be analysed scientifically, and so in this section only findings derived from formal experiments are considered.

Written surveys have been undertaken in the United Kingdom after pilots have used PAPI operationally at Heathrow or Gatwick Airports (Brown 1979). The partial results of the survey at Gatwick were published repeatedly (VAP 1978; CAA 1978; Brown 1979, 1980), and it was partly on the basis of these results that PAPI was introduced to ICAO as a contender for inclusion in Annex 14. It was not until November 1980 that the fuller results from the Heathrow evaluation were made available (VAP 1980).

The first survey at Gatwick Airport in 1977 was conducted over a period of 9 months. About 200 opinions were collected from respondents by mail or from collection points at the Airport, and replies to three of the eleven questions were published (Brown 1979; CAA 1978). The results, broken down into categories of experience with PAPI (which were obtained from one of the three questions), are reproduced in Table 1. (Note that in Question 9 the "same" responses reported in the source material have been excluded here because this category was not provided on the original survey form—see CAA 1977.)

As can be seen from Table 1, a high percentage of pilots preferred PAPI to Red-White VASIS for ease of acquiring and maintaining an approach slope (85%, Question 8) and almost all respondents thought that the touchdown aiming point was better defined (92%, Question 9), especially those pilots who had made five or more approaches (97%).

TABLE 1

Percentages of pilots' replies to two questions expanded over pilot experience with PAPI from the 1977–1978 Gatwick survey (questions from CAA 1977; results collated from CAA 1978; Brown 1979).

	Number of approaches by each pilot	Easier	Same	More Difficult
8. *Ease in using PAPI to acquire and maintain visual approach slope compared with VASIS?*				
	1 or 2	77	19	4
	3 or 4	89	11	0
	5 or more	91	7	2
	All reports	85	13	2

	Number of approaches by each pilot	Yes	No
9. *Did you consider PAPI to give better definition of touchdown aiming point than VASIS?*			
	1 or 2	86	12
	3 or 4	91	6
	5 or more	97	3
	All reports	92	7

Similarly, the majority of pilots preferred PAPI (in both a one bar and a two bar form) when compared with Red-White VASIS at Heathrow Airport, but the percentages were generally lower. The figures covering all questions obtained from the Heathrow evaluation were tabulated (VAP 1980, Appendix A). In this later evaluation 71% of pilots chose the "better" alternative when asked a question similar to 8 above (see Table 1) and 66% chose "better" for Question 9 (VAP 1980, Appendix A). Correspondingly, the number of favourable comments received outweighed the unfavourable, and overall 84% of pilots favoured PAPI, 13% thought they were the "same" and 3% preferred Red-White VASIS.

It could be concluded from these results (even without a statistical test) that PAPI was outstandingly preferred to Red-White VASIS, were it not for various experimental details which may have biased the respondents. For instance, PAPI was introduced into the literature available to pilots before and during the periods of evaluation. Many examples containing laudatory comments exist (e.g. *Air Clues* 1975, 1978; *Airports International* 1976; *Aircraft Engineering* 1979; Brown 1979; *Flight Safety Focus* 1976, 1978; Green 1978). Further, the Civil Aviation Authority published information circulars (CAA 1977, 1979, 1980) which outlined in detail the presumed advantages of PAPI, and published the general findings of previous evaluations. Parts of these circulars have been collated in Appendix B of this current report. The circulars also contained a copy of the questionnaire.

The questions themselves, unfortunately, may also have biased pilot's responses. The use of the terms "better" and "worse" (CAA 1979, 1980) imply a value judgement applied by the Authority in favour of one VASI over the other; it may have been fairer to ask the pilots for their personal preference instead. The possibility of response set and the "halo" effect (Oppenheim 1966) influencing the opinions was also apparently not accounted for (e.g. by interchanging the positions of the categories on some of the forms). In order to evaluate the acceptance of PAPI by pilots it would be best to refer to data which were not subject to the influences outlined in this and the preceeding paragraph. However, as far as can be ascertained, pilots were required to answer whether PAPI was "better" than Red-White VASIS in almost all questions asked in the various surveys.

Modified slot-type boxes were used in a preliminary experiment assessing the potential of PAPI (20′, 20′, 20′) for replacing 3-BAR Red-White VASIS conducted by the FAA (Paprocki

1977). Even though the transition zone was too broad, the opinions expressed were encouraging. Ten of the fourteen test pilots who used PAPI at night thought PAPI was "better", one thought them to be the "same" and three indicated PAPI was "worse" than 3-BAR Red-White VASIS. The pilots relied on their memory of prior experience with Red-White VASIS. This high level of approval was not sustained in later FAA trials.

In one later evaluation of PAPI using sharp transition boxes undertaken in Atlantic City, 7 from 12 test pilots preferred PAPI and 5 rated it the same as 3-BAR Red-White VASIS, both by day and by night (VAP 1980, Appendix C). In another study, by Castles (1981), PAPI (20′, 30′, 20′) was evaluated by operational pilots of transport aircraft. The interim results indicated that PAPI was preferred overall to Red-White VASIS (number of bars not indicated) by the majority, but again a large proportion (39 percent) did not rate PAPI as better. These results are discussed in more detail further on (Section 4.1.2). A third study (FAA 1981) concentrated upon a two box system and is also discussed further on (Section 3.4.2).

3.4.2 Flight trial data

Smith and Johnson (1976) reported that PAPI had been evaluated at five airfields in the United Kingdom with a wide variety of aircraft, involving about 4000 approaches. Some of these approaches were tracked by kinetheodolite and three when pilots used PAPI and five with Red-White VASIS were illustrated in their 1976 report. The PAPI trajectories appear less variable than those with Red-White VASIS, but because small unequal numbers of trials are shown without metrics describing the paths, it is not possible for others to judge whether this apparent difference is significant. Further, this illustrative evidence is not comprehensive enough to determine whether the trend was characteristic of all (or at least most of) the flights undertaken either in the general evaluation or in the tracked approaches.

Smith and Johnson also did not indicate which aircraft were flown when the trajectories were obtained, whether the pilots were military pilots, test pilots, or from commercial backgrounds, or their previous experience with VASIs. The latter two shortcomings also limit an assessment of the flight trial data reported by Paries (1979) which contains the most extensive controlled data about PAPI currently available.

In Paries' paper nine approaches to PAPI (10′, 10′, 10′) and eight to Red-White VASIS by Nord 262 aircraft (medium-weight) are reproduced in tabular and graphical form. Although Paries did not statistically compare the performance between the conditions, the average slope maintained and a measure of angular deviations for every trial were published. Unfortunately, there was insufficient information reported by Paries about the experimental methods for the current author to statistically analyse these results, *post hoc*. PAPI pilots flew closer to the nominal 2·7° glideslope (mean: 2·6166°, SD: 0·0514° than did Red-White VASIS pilots[1] (mean: 2·5625°, SD: 0·0725°), but this difference is slight and may not be statistically significant. If the effect is robust, it may not be attributable to generic properties of the VASIs. From previous literature claims (e.g. Smith and Johnson 1976), it is not unreasonable to expect that pilots will fly closer to the nominal glideslope with PAPI. However, Red-White VASIS is notoriously difficult to align, even with lens-type boxes (Johnson and Smith 1971) as were used in Paries' experiment, and a slight variation from the nominal slope may account for differences in the average slope maintained.

The important parameters of variability from average glidepath were also reported by Paries (1979) under the heading "Ecart moyen par rapport à l'angle moyen". A literal translation of this heading, viz. "mean deviation from the mean angle of approach path", suggests that the figures represent a mean arithmetic deviation presumably from the nominal glidepath.[2] The figures most commonly quoted from Paries' (1979) report are a mean deviation of 0·07° for PAPI and 0·13° for Red-White VASIS and the samples from which the means were derived

[1] N.B. A subsequent personal communication from Paries, mentioned that only one pilot (commercial) flew all seventeen approaches.

[2] N.B. Paries has recently written to say that these figures are the standard deviation from the average approach slope of each trajectory.

probably will prove to be statistically different. The variance (calculated by the current author) in Paries' deviation scores was also greater for Red-White VASIS than for PAPI (SD = 0·0506, SD = 0·0222, respectively). These results suggest that, for medium-weight aircraft when PAPI sector sizes are 10 minutes of arc, pilots diverge less from the nominal glideslope and follow it more consistently than with Red-White VASIS.[3] However, statistical tests are required for confirmation when the exact methods used to collect the data are known. It is important to note that the sectors of PAPI (10′, 10′, 10′) can be geometrically inscribed inside the main corridor of Red-White VASIS within its transition zones. However, the lowest signal changes of both PAPI (20′, 20′, 20′) and PAPI (20′, 30′, 20′) enter the inner edge of the "too low" transition of Red-White VASIS at 0·61 and 0·46 n miles from the nominal aiming point, respectively.

A brief description of trials undertaken in the USA was presented to ICAO (VAP 1980, Appendix C) in November at the last Working Party meeting considering PAPI. Flight trials using FAA test pilots flying four aircraft types (of which Convair 880 was the biggest) were conducted to determine how accurately PAPI (20′, 20′, 20′) signals could be followed. The phototheodolite data from 72 approaches were condensed into range segments (200 ft) and the mean position and standard deviations calculated. Linear regression lines were then drawn through the mean, ± 1 SD and ± 3 SD values over range. From these lines it was predicted that almost all aircraft (99·75%) would remain within about ± 22′ from the nominal glideslope.

These results show a symmetrical distribution (as do the mean measures of variability reported by Paries (1979)) which implies that the pilots flew equally as often on each side of the nominal glideslope. However, Paries (1979) reported that the pilots[3] in his experiments tended to fly on the lower bound of the "on glideslope" sector, and this trend was clear in the graphs of flight paths, although not in the data.

Further the figure of ± 22′ obtained in the USA implies that pilots would not be expected to see PAPI signals when either all white or all red, i.e. the pilots always remained within two signal changes from the glideslope (one high or one low) and would thus see only three of the possible five signals. This is an unusual finding in VASI research; in most experiments, and not only those assessing PAPI, pilots do deviate through the outermost corridors at some time (see for instance the illustrations in Lewis and Mertens 1979*a*; Paries 1979). It is therefore distinctly possible that the averaging process used in obtaining the regression lines did not take adequate account of wide divergences and so these most important events could remain obscured by the statistics.

Another fundamental difficulty with assessing the performance of PAPI in the USA trials arises from the absence of a control or comparison condition (such as "no aid", T-VASIS, or Red-White VASIS). It cannot therefore be judged whether or by how much PAPI influenced the pilots' tracking accuracy in this experiment.

The accuracy of touchdown point was reported to be "superior with PAPI than with Red-White VASIS" by Brown (1978). In 1980, supporting figures were published which showed that the scatter of touchdown points obtained with PAPI in some (unspecified) UK trials ranged between 290 to 470 m (970 to 1570 ft) compared with 300 to 600 m (1000 to 2000 ft) for Red-White VASIS (Brown 1980, VAP 1980).

It is interesting to note that the range for PAPI is substantially less than that which can be derived from the standard deviations obtained in a simulator experiment by Bisgood, Britton and Ratcliffe (1979). (The relevant conditions in this comparison are reproduced in Table 2—note particularly A3 and A4 flat profiles.) Although there is considerable risk in comparing real life values with those obtained in a simulator it is worthwhile noting that Bisgood, Britton and Ratcliffe (1979) controlled their experiment and included the conditions of night-time and wind which are excellent for testing the worth of VASIs. If the simulation was adequate, Brown's results may prove to have been collected under less demanding flying conditions.

Brown (1980) also quoted figures for HOT of ± 5 ft for PAPI and ± 20 ft for Red-White VASIS (presumably measured from the nominal glidepath). *Prima facie*, there seems to be a huge difference in efficacy between the aids, despite the absence of a statistical test. However, these figures cannot be evaluated further without detailed information about the experiments (e.g. aircraft type, pilot category, number of approaches, time of day, runway, weather conditions, etc.) and the mathematical methods used during derivation. As an illustration of this

[3] N.B. These results refer to only one pilot's performance.

TABLE 2

Touchdown performance on simulated runway with PAPI represented. Results from Bisgood, Britton and Ratcliffe (1979). (All values in feet.)

Type of approach	Flat Profile: Number of approaches	Flat Profile: Distance from threshold Mean	Flat Profile: Distance from threshold SD	Normal Boundary Layer: Number of approaches	Normal Boundary Layer: Distance from threshold Mean	Normal Boundary Layer: Distance from threshold SD
A1 Automatic approach and landing: Decision height 50 ft	26	1,292	241·2	20	1,411·5	339·9
A2 ILS coupled approach to 200 ft, manual landing: Decision height 200 ft	58	1,413	485·7	45	1,489	503·4
A3 Manual ILS approach, manual landing: Decision height 300 ft	41	1,549	484·5	47	1,551	468·3
A4 Non-precision approach "talk-down", manual landing: Decision height 400 ft	23	1,395	358·6	24	1,440	509·8

latter point, Cumming (1962) reported similar magnitudes for day-time Red-White VASIS HOT, but the distribution of the raw measurements was skewed and the data were normalised by a logarithmic transform. Brown (1980) reported a symmetrical distribution.

At the time of writing this paper, a two box installation of PAPI was being tested at the FAA Technical Centre and preliminary results have recently been published (FAA 1981). Trajectories of Aero-Commander aircraft flown by FAA test pilots approaching to PAPI by day and night were obtained from radar tracking. The trajectories show some interesting trends with quite marked oscillations, particularly near the runway, but because the FAA had not completed their planned trials nor had the opportunity to discuss these results formally, no further analysis is warranted here. The pilots participating in these tests also completed questionnaires about PAPI, and their answers are tabulated in the report, again without comment by the FAA. However, ten pilots rated PAPI as better, nine as the same and two as worse than SAVASI.

4. EVALUATION OF ERGONOMICS AND THE ABILITY TO FULFIL OPERATIONAL REQUIREMENTS

4.1 Siting

The site (or position) of a VASI alongside a runway can influence the operational performance of pilots approaching to land. This siting factor and its significance for each of the three VASIs is considered below.

4.1.1 Threshold clearance

An operational requirement which arose after the acceptance of Red-White VASIS and T-VASIS into the ICAO standards was the necessity to provide guidance to the pilots of wide-bodied commercial aircraft (e.g. B747, DC-10). Achieving an adequate safety margin for the aircraft wheels over the threshold has become a concern because the pilot's sitting eye height is a considerable distance above the wheels in these aircraft compared with older types. (For instance typically a pilot's eyes are at least 44 feet (13·4 m) above the wheels according to Brown (1980) and to the Flight Crew Instructor/Training Manual for B747 aircraft (Popple 1980).) If the pilot flies a conventional 3° approach aimed visually at the usual touchdown point, the wheels of wide-bodied aircraft will not clear the threshold by the ICAO-specified safety margin of 9·1 m (30 ft).

Pilots of wide-bodied aircraft may achieve suitable threshold clearance by flying either a 'one-dot' high or 'two-dot' high indication from T-VASIS at an approach slope close to 3° because these T-VASIS signals originate from sources further upwind. However, theoretical clearance cannot be achieved with Red-White VASIS unless the installation is moved upwind (which apparently was an unacceptable solution) and therefore further refinement in the basic configuration was implemented.

The solution devised for Red-White VASIS was to add an extra bar upwind to provide another approach channel terminating at some distance further along the runway (see Gates 1970). However, because of alignment difficulties caused by the pink transition zones, the third bar is not easy to adjust and usually in practice a 3·5° slope is defined instead when standard slot-type boxes are installed (Smith and Johnson 1976). This nominal glideslope can be lowered by using sharper transitions, achieved with either modified standard boxes (Gates and Paprocki 1972*a*) or lens-type boxes. For instance, all the standard boxes could be replaced, or one set of lens-type boxes could be installed for the middle bar (Smith and Johnson 1973).

It has been suggested that a PAPI bar sited 395 m from the threshold of a standard non-sloping runway where there are no obstructions protruding into the approach space will provide adequate threshold clearance for wide-bodied aircraft (AGA 1981, Appendix B). This site provides a minimum clearance of 5·9 m for the wheels of B747s which is less than the 9·1 m specified by ICAO; the clearance specification may be achieved by siting PAPI 460 m (1510 ft) upwind of the threshold. (Note that this value is based on an angle of 2°48′ for the lower bound of the PAPI approach sector, and an allowance of 44 ft between the pilot's eyes and aircraft wheels.) For a 39 ft eye to wheel height (the figure used by VAP/9), PAPI should be sited 429 m upwind. Nevertheless, other considerations, which are discussed below, also constrain the position of VASIs and a straight forward repositioning of PAPI to allow for regulation threshold clearance does not seem to be tenable.

4.1.2 ILS compatibility

Moving the aiming point of a VASI upwind is useful to provide threshold clearance, but because the ILS aerial on many wide-bodied aircraft is mounted about halfway between the wheels and the pilot's eyes, the ILS information may not then correspond with the VASI signals. (Conventional aircraft (e.g. B707, DC-9, etc.) usually have eye to aerial dimensions of about 1 m and therefore the two sources of glidepath information are compatible for standard installations.)

The large eye to aerial distance in wide-bodied aircraft is not disadvantageous when T-VASIS is being used because an "on-glideslope" indication from the ILS instrument corresponds to the T-VASIS "one-dot" or "two-dot" high approach path necessary to achieve wheel clearance, and the information remains linked for the entire approach (Smith and Johnson 1976). (This relationship is theoretical and in practice small variations may occur because the ILS signals can diverge slightly at range.) Indeed, one of the features of the T-VASIS design is the facility to fly slightly non-standard approach paths which are aimed at different points along the runway.

The addition of the extra bar in Red-White VASIS makes the ILS signals impossible to harmonize with the visual signal over the entire upper approach corridor because the aiming

point has been moved upwind of the ILS origin and the ILS signal will change at different ranges even during a constant 3·5° approach (Smith and Johnson 1976), or indeed a 3° approach.

The siting solution for PAPI is not straight forward principally because PAPI signals radiate from a line perpendicular to the runway edge and can therefore provide only one aiming point which has to accommodate both conventional and wide-bodied aircraft classes. For conventional aircraft, PAPI needs to be sited close to the ILS origin for the two sources of glideslope information to be compatible. From the author's calculations, PAPI units sited at 460 m from the threshold (which gives threshold clearance on a standard flat runway) enables the ILS/PAPI compatibility[1] to be maintained, theoretically, to about 200 m past the threshold for the wide-bodied jets (using 5·9 m as the eye to aerial height). Unfortunately, the guidance for conventional aircraft will then be incompatible from a distance of 1400 m before the threshold which is equivalent to a height above the ground of 280 ft (85 m). Two solutions to accommodate all aircraft types have been suggested and these involve either modifying the sector widths and resiting the bar, or adding an extra bar of boxes further upwind of the ILS origin (a two bar form). As already mentioned above, this latter suggestion has not proved successful during flight trials, nor in a simulator experiment (Lewis and Mertens 1979*a*). The reasons are discussed more fully in Appendix A.

The compromise most popular at the time of writing for overcoming ILS/PAPI harmonisation difficulties is to widen the central sector to 30′, leaving the outer sectors at 20′ (Brown 1980). Additionally, Brown stipulated that the nominal glideslope should be lowered by 5′ to 2°55′ instead of the more usual 3°. It has been reported that if this PAPI configuration is located between 390 to 440 m (i.e. 75 to 125 m from the ILS origin) ILS compatibility will be maintained for wide-bodied aircraft to within 300 to 400 m of the threshold (VAP 1980, para 1.4.27). However, to maintain threshold clearance of 9·1 m, a location of at least 490 m is required (22·5 cot 2·63°), i.e. a distance 175 m upwind of the effective ILS origin (nominally 315 m). ILS compatibility for wide-bodied aircraft may be degraded somewhat again by this site. Threshold clearance would be adequate for conventional aircraft using either PAPI site but ILS compatibility decreases as the site is moved upwind. For PAPI (20′, 30′, 20′) sited at 390 m, compatibility for conventional aircraft will be achieved almost to the threshold whereas at a 490 m site the compatibility is lost at a range of 762 m before the threshold. The equivalent height above ground where the signals become incompatible is, theoretically, 160 ft (50 m) at this latter site, an improvement over the 280 ft achieved with PAPI (20′, 20′, 20′) (see above).

The simplified calculations presented above do not account for practical considerations such as obstacle clearance surfaces, runway length, runway slopes or fluctuations in the ILS glideslope angle. If these are considered then further compromise in siting will be required at particular runways and it has been suggested that the wheel clearance over the threshold should be "degraded" where necessary (AGA 1981, Appendix B, para 7.1). However, in the opinion of the current author the performance data available are too incomplete to sustain the lower limits proposed to AGA (AGA 1981). There are also discrepancies between the siting figures presented to VAP/9 and those calculated here (e.g. in the order of 50 to 100 m along the runway for wide-bodied aircraft) which cannot be explained by the different eye to wheel heights used (39 ft compared to 44 ft respectively). Possibly, different assumptions were made about the compatibility criterion or the standard runway dimensions, etc. Although the PAPI (20′, 30′, 20′) suggestion produces a compromise which may be more satisfactory than PAPI (20′, 20′, 20′) for both aircraft classes, nevertheless, it is quite obvious that siting issues still remain to be sorted out. Furthermore, at the time of the ninth VAP meeting it seemed that the PAPI (20′, 30′, 20′) alternative was merely a paper suggestion which had not been formally tested.

Since then, PAPI (20′, 30′, 20′) has been operationally evaluated at Newark International Airport where the row was sited 300 ft (91·5 m) beyond the ILS giving threshold clearance of 21 ft for B747s and 62 ft for smaller transport aircraft (Castle 1981). While overall more pilots clearly preferred PAPI, nearly as many (and for some questions more) pilots had no preference for either system. In particular, 40 per cent of pilots rated PAPI as having better ILS coincidence than Red-White VASIS, but the majority (60 per cent) indicated that PAPI did not have the

[1] N.B. The criterion for compatibility was based on the range and height where the lower transition edge of the PAPI central approach sector meets the middle of the "on slope" ILS signal. The ILS was represented by straight lines emanating from the nominal origin.

advantage. Similar preferences were reported for the usefulness of touchdown aiming point and pilots were divided almost equally in opinion about whether PAPI did or did not provide ease of maintaining an approach angle in comparison to Red-White VASIS, perhaps indicating that PAPI guidance deteriorates when the central sector is widened. Since 30 per cent of the sample comprised opinions from pilots of wide-bodied aircraft it would be interesting to discover if these opinions of PAPI correlated with aircraft type. This was not stated by Castle in his preliminary report (Castle 1981).

A number of ergonomic difficulties may arise if the 20′, 30′, 20′ sector configuration is accepted along with the standard 20′, 20′, 20′ PAPI. For instance, widening the central corridor by 50 per cent decreases the sensitivity of the feedback and may correspondingly degrade tracking accuracy, especially at the beginning of an approach. Further, some pilots of smaller, but common, aircraft with 1 m eye to ILS aerial dimensions may be required to use the two PAPI configurations on successive occasions. Transfer of training between the two may cause interference which reduces tracking accuracy on each system. It apparently remains to be assessed whether these predicted losses in accuracy due to changing the sensitivity occur, and if they do, whether they have operational significance.

Also of concern is the possibility that, on runways where PAPI is installed upwind of the ILS origin, all aircraft will be required to touchdown further from the threshold. At airports where the taxiways have been positioned to assist a pilot to leave the runway quickly, it is possible that some pilots who are familiar with the particular airport topography may be tempted to land short of a displaced aiming point to hasten their exit from the runway. Consequently there is a risk that pilots may disregard the VASI signals when on late finals. The tendency of pilots to facilitate quick exits from runways has been previously implicated as a cause of undershooting (Hartman and Cantrell 1968).

4.1.3 Compatibility with subsidiary ground traffic systems

A good deal of space, unobstructed by taxiways or crossing runways, is required by both T-VASIS (450 m or 1500 ft) and Red-White VASIS (420 m or 1400 ft) in its three bar form because the boxes are located longitudinally down the side of the runway. T-VASIS has been criticised for this aspect of its design (Smith and Johnson 1976; Hald 1980). However the criticism ignores the wide tolerance of spacing which may be incorporated without unduly affecting the sensitivity of the system. Where obstructions do interfere with the location of leg units the standard layout can be altered with very little effect on the performance of T-VASIS (Baxter, Cumming, Day and Lane 1960) and accordingly the ICAO standards provide for adjustment in the separation and cut-off angles of the constituent boxes.

Red-White VASIS is also adaptable but the minimum separation between the wing bars is constrained by the visual ability of the pilots. The smaller the distance between the bars, the harder it is to distinguish the two separately within the ICAO-specified range of the runway. The wider the distance between the bars, the larger the approach channel, and the guidance obtained becomes less useful. Originally, systems with two bars were specified with 1000 ft (305 m) separating them (Sparke 1958), but later this was amended to 500 ft (150 m) by RAE according to Baxter, Cumming, Day and Lane (1960) and eventually 700 ft (210 m) was accepted by ICAO (Annex 14). Similarly, two bar versions of PAPI suffer from reduced visibility and merging of the signals (see Appendix A).

4.2 Atmospheric Effects and Viewing Conditions

The effect of ambient meterological conditions on the integrity and visibility of VASI signals depends upon, amongst other things, the wavelengths of the light used in the signal and the discrimination required of the pilot. A VASI system in which perception of the primary signal relies upon discrimination between two colours is more prone to interference induced by meterological conditions (Clark and Gordon 1981) than a VASI which relies upon the pilot

registering only the presence or absence of light. The colour of objects and lights seen at a distance is particularly susceptible to alteration because atmospheric aerosols selectively absorb and scatter light (Middleton 1952; Sparke 1958; Watkins 1971).

When the atmosphere contains water droplets (e.g. in conditions of rain, mist or fog), particles of dust or smog, or a combination of these, selective absorption and scattering can make white light appear orange/red commonly (Middleton 1952) and red light desaturates appearing more orange than red according to Sparke (1958). These effects result in the colours of Red-White VASIS signals being difficult to distinguish. On other occasions, depending on the composition of the aerosol, light sources may change colour and obtain a halo. For instance a white light can appear yellow with a blue halo and red light can appear a longer wavelength red with an orange halo (Watkins 1971). At a distance the halo colour usually predominates. These effects have been observed with Red-White VASIS at Darwin where atmospheric dust is commonplace and scattering changed the appearance of the white light to blue and the red light to orange (Watkins 1971). This installation was subsequently removed from service.

Scattering effects also occur in haze and can influence visual perception especially if the position of the sun is unfavourable. For instance, when an approach is made into sun and the atmosphere is hazy, the colours of Red-White VASIS may be indeterminate (Sparke 1958) at ranges greater than 1·5 n miles (about 3 km) according to Morrall (1960). Further, Smith and Johnson (1976) reported that under sunny conditions (a bright sun or a sun low in the sky) a pilot in the "on slope" channel of Red-White VASIS may see a red/pink signal from both wing bars instead of a red-over-white when greater than 2·5 km (1·3 n miles) from touchdown. Hazy conditions at night can also scatter Red-White VASIS signals, making the colours difficult to distinguish at ranges greater than 3 n miles (5·7 km) according to Morrall (1960).

Light ground fog can scatter light sometimes degrading VASI signals and these effects deserve special mention. The redistribution of light from scattering results in the light from the Red-White VASIS segments mixing, desaturating the red and reddening the white signals, so that the perceived transition zone widens and pilots may have difficulty in distinguishing the colours. Scattering of emitted light from the boxes of T-VASIS may cause all the leg units to be seen at once although the lights appropriate to the pilot's position on glidepath are brighter. The circumstances which can give rise to this situation seem to occur rarely in Australia and DCA had only three reports in eight years of records by the end of 1971 (DCA 1971).

The use of colour-coding in the primary signals probably makes PAPI susceptible to effects from scattering by aerosols which have been already observed in Red-White VASIS. Although the narrowing of the transition zone on-axis will be advantageous in some (undetermined) favourable viewing circumstances because pilots will have to distinguish between only two rather than three, sometimes merging, colours, the use of darker red filters in PAPI makes perception of the signals more susceptible to degradation by scattering from white light (Clark and Gordon 1981). Of most concern is the possibility that the perceived transition zone will widen and the lights may appear pink or pinkish white or white; in the worst case, scattering could cause the colours to be indistinguishable.

The absence of colour coding in the primary T-VASIS signals means the system is not as susceptible to adverse viewing and atmospheric conditions because the pilot needs to deduce only the presence or absence of a signal. When the pilot is low enough on approach to warrant a red signal it acts as an extra warning of "danger" but the colour itself is not the primary signal.

4.3 Slots Versus Lenses

Two different principles have been used in the design of VASI boxes; either the signal exits from the box through a slot or instead exits through a collimating lens at the front of the box. Slot-type boxes incorporating a simple afocal source were originally used for both TEE and Red-White VASIS. In Red-White VASIS a red filter was placed between the source at the far end of the box and the horizontal exit slot at the other end. In the leg boxes of TEE, opaque blades restricted the light emitted to a range of elevation angles. Later, both TEE and Red-White boxes were modified.

The development of T-VASIS from TEE retained the slot principle. The light sources were replaced with collimating lamps and another blade was introduced nearer to the lamps. The

original blade was moved closer to the exit end of the box. This use of two blades allowed better definition of the beam cut-off, and the lower red sector could be easily added where required. Additionally, the available light was used more effectively than in the initial design.

The slot-type box produces a visible luminance gradient between the "on" and "off" signals. T-VASIS provides the pilot with "fine tuning" if he desires it by taking advantage of this gradient. When on late finals the pilot can see a glimmer or "pinprick" of light emitted from the first "too high" and "too low" leg units and the intensities of these signals change depending on the direction of any divergence from glidepath. (The luminance increases from the box corresponding to a glidepath divergence while the light emitted from the other box decreases.) This feature was considered desirable by pilots and thus was emphasised in the T-VASIS design (Cumming and Lane 1957*b*).

Many later Red-White VASIS boxes did not retain the slot principle, but instead have been built using the lens principle. This design incorporates objective lenses at the front of the box. One or two filters at or near the focal point of each lens produce the red segments (Johnson and Smith 1971). Advantages of the objective lens boxes included an improvement in light collection and more effective direction of the light than in the slot-type design. In addition, the length of the VASI box may be reduced and the transition zone between the red and white sectors can be minimised by using only one filter which is placed in the common focal planes of the objective lenses.

The sharper cut-off of the Red-White VASIS signals achieved from using lenses allows the three bar system to be better aligned during installation and the corridors have similar approach slopes for both wide-bodied and regular aircraft (Smith and Johnson 1973). Further, the sensitivity of Red-White VASIS using lens-type boxes is practically constant over range because a corridor with almost parallel sides can be defined when the transition zone is narrow (compared with slot-type boxes producing wide transitions and therefore a divergent corridor), and this feature was not considered as disadvantageous during trials (Johnson and Smith 1971). (Although in another experiment when the transition zone was reduced, pilots did fly a lower average approach path than with the wider zones from standard boxes (Gates and Paprocki 1972*a*).) However, lens-type boxes have the disadvantage of scattering light when dust or moisture deposits on either surface of the objective lenses. (Scattering could be reduced if the lenses were adequately protected from the environment but this feature has not been included so far.)

Dirty lenses scatter the emitted light producing degradation in the colours of Red-White VASIS signals. Further, the intensity of the emitted light may also be reduced, resulting in a decreased visual range of the system. Lens-type boxes have also been installed at some airports (e.g. Singapore) in the T-VASIS configuration. Scattering of light from dirty objective lenses can cause all the leg lights to be visible to a pilot late on approach. Even though the lights which should not be seen when the pilot is at any particular elevation are considerably dimmer than the correct lights, some pilots have found the signal confusing (Jones 1977).

Scattering effects caused by dirty lenses are a serious problem and the use of lens-type boxes has been criticised many times in connection with a number of VASIs because they fail "unsafe" (e.g. trisector aids, Sparke 1958, Clark 1968; Red-White VASIS, Calvert 1978; T-VASIS, Leevers 1978*a*, Hald 1980). Only slot-type boxes are approved for T-VASIS use in Australia. A licencing agreement covers the manufacture in Australia, but in some other countries where the agreement does not apply, lens-type boxes have been marketed as suitable for T-VASIS installation. Red-White VASIS is at a particular disadvantage because many lens-type boxes have been installed at airports. Calvert (1978), recognising this problem, recommended to ICAO that only slot-type boxes should be used to generate Red-White VASIS signals.

The boxes of PAPI also incorporate objective lenses, although the construction and optical design is slightly different from the lens-type Red-White VASIS boxes described above. (Objective lenses are required to produce the small transition zone specified in the PAPI design.) It was thought that Red-White VASIS boxes could be modified to achieve PAPI specifications (Brown 1978), but according to Paries (1979) slot-type boxes are incompatible and cannot be modified. Lens-type boxes require substantial changes to the structural rigidity of the boxes and to the setting precision of the elements to obtain the precise settings required (Paries 1979), although this is reported not to be an expensive undertaking (VAP 1980). The FAA have also had difficulty in modifying Red-White VASIS boxes (type specified as "standard") to achieve the specifications for PAPI and could not obtain the narrow transition zone (VAP 1980, Appendix C).

Lens-type PAPI boxes suffer the same disadvantages from scattering light as do the lens-type boxes used to generate Red-White VASIS signals. Moisture on the objective lenses can destroy PAPI signals. Hald (1980) reported that twice during experimental trials when condensation formed on the PAPI lenses, four completely white emitted signals resulted, obliterating the proper red signals. Ambiguous pink signals from all four boxes have also been seen for a short duration when PAPI is first switched on after periods of rain or high humidity (VAP 1980, Appendix C). Dust or dirt on the lenses also changes the colour of PAPI signals. Clark and the current writer observed a widening of the transition zone when PAPI objective lenses were deliberately dirtied during a laboratory experiment (see Clark and Gordon (1981) for methodological details). The degradation was sufficiently severe to produce a pink signal over the entire angular extent of PAPI, but the magnitude of the effect in the field would depend on how dirty the lenses became. A way to overcome the unwanted moisture that may accumulate on PAPI lenses has been suggested (Hald 1980), yet at the same time the method may exacerbate the problems caused by dust collection (Clark and Gordon 1981).

4.4 Installation and Maintenance

Smith and Johnson (1973, 1976) have emphasised the requirement for VASI boxes to be easily installed and maintained. They reported that a significant amount of maintenance and checking was required to ensure that the corridor boundaries of Red-White VASIS remained properly aligned. One reason why such attention is necessary presumably arises because the older box designs still in service were not built sturdily enough to resist strong wind or blast from passing jets' efflux (Johnson and Smith 1971). The major reason, however, is probably related to the perception of the coloured signals.

The pink transition zone has caused problems in aligning the inner bounds of the corridor in 2-BAR Red-White VASIS because "colour contrast" effects (more properly the viewing conditions and the effects of any atmospheric attenuation—Clark and Gordon 1981) alter the perceived width of the zone (Brown 1978). Often the zone appears to be "much deeper than the 1/2 degree that is often assumed" (Smith and Johnson 1973) and was estimated to appear as wide as 3/4° in sunny conditions (Smith and Johnson 1976). Alignment of the two bars in the standard Red-White VASIS is difficult to achieve because the inner boundary where the pink changes to red is not easy to see, while the problem is accentuated by the extra bar in the three bar form (Smith and Johnson 1973, 1976; VAP 1978).

The perception of the colour boundaries due to effects such as those mentioned above (e.g. the brightness of viewing conditions, atmospheric attenuation, etc.) could also interfere during alignment of PAPI boxes. However, rather than relying upon the conventional flight checking techniques which use aerial observation, PAPI boxes have been designed with spirit level mounts so that the alignment can be achieved on the ground without visually checking the colour zones. An estimate of the accuracy of this ground-based method has not been published, but it depends on the precision with which the mounts are aligned with the optical elements inside the box. Nevertheless, the alignment perceived by pilots will still be dependent upon the atmospheric and viewing conditions and the physiological state of the observer.

The ground-based installation methods used with PAPI could be profitably extended to other VASI types, thus reducing the expense of installation. Clark (1980) has suggested using optical techniques which might improve the methods used when installing T-VASIS, and these could possibly be used with other VASIs.

T-VASIS has also received criticism from Smith and Johnson (1976) because they thought it requires substantial maintenance. The criticism, however, appears to have been based upon the one anecdotal account mentioned in their paper. Misalignment of T-VASIS is not typical in Australian experience; the boxes require only a modicum of maintenance with perhaps a small adjustment (1′-2′ of arc) in one box from twenty over a period of six months (Popple 1980).

4.5 Tracking Guidance

There should be sufficient information invested in VASI signals to allow the pilot to track the desired flight path accurately. Several factors of VASI design have been recognised as influencing pilots' ability and these are mentioned below with an appraisal of the three VASIs under consideration.

4.5.1 Categories of information

In general, the precision of the feedback provided influences the ability to track accurately. Of particular significance to VASI design are the results of experiments by Hunt (1961, 1964).

Hunt's experiments showed that a substantial reduction in tracking error could be achieved when the number of informational categories was incrementally increased using 3, 7 and 13 categories and a continuous display. The relationship between tracking error and the number of categories was non-linear and monotonic no matter whether the task was "easy" or "difficult". A further finding in both studies showed that fewer corrective control movements were made by subjects in the 7 category condition when compared with subjects in the 3 category condition for an "easy" task. The number of control movements increased under a "difficult" task with 7 categories but decreased when 3 categories of information were presented; a fact that Hunt (1961) attributed to "... a feeling of futility on the part of the subject, i.e., the task was so difficult that the subject effectively "gave up"."

Cumming (1962) recognised the similarity between the task in Hunt's experiments and the tracking task required of a pilot making an approach guided by a VASI. When applying the results, Cumming predicted that the 3 categories of information provided by Red-White VASIS (two bar) probably would not give enough feedback and therefore pilots' tracking the glideslope would be relatively inaccurate. (The pink transition zones in Red-White VASIS were not regarded by Cumming (1962) as steps of information but rather as regions of uncertainty between categories.) Moreover, under critical circumstances a pilot might unconsciously accept a lower standard of performance than otherwise (although one would not expect him to "give up").

T-VASIS was designed with seven primary categories of information (disregarding the graduated red undershoot signals) on the basis of Hunt's experiments (Cumming 1962). T-VASIS should therefore enable superior accuracy in tracking, being closer to that obtained with a continuous display of the error feedback than that with Red-White VASIS. Again, from the results of Hunt's experiments it can be predicted that the influence on tracking performance of the five categories provided by PAPI will most likely lie between that of 2-BAR Red-White VASIS and T-VASIS.

However, factors other than the informational categories provided undoubtedly influence tracking. For instance, Lewis and Mertens (1979*a*, 1979*b*) found that performance of pilots was not as accurate when using a two bar form of PAPI which provided nine categories of information as when pilots were guided either by 3-BAR Red-White VASIS (with four categories) or T-VASIS. (The 2-BAR PAPI used in these experiments is described in Appendix A.) Lewis and Mertens suggested that the ease with which the display was interpreted played a significant role in contributing to their results.

4.5.2 Interpretation of the signals

"It is important to provide the pilot with information in a form that he can easily interpret".

Cumming (1962).

This recommendation by Cumming was based on the sound ergonomic principle, stated by Welford (1960), that people who are busy should be provided with information that requires a minimum of interpretation.

The importance of using director-type displays in VASIs has been demonstrated by research undertaken in a T-2C simulator by Lintern, Kaul and Collyer (1980) (see also Kaul,

Collyer and Lintern 1981). These authors were interested in the effect on performance obtained by augmenting the information from a Fresnel Lens Optical Landing System (FLOLS) used during aircraft carrier landings. They found that experienced Naval pilots could use an augmented FLOLS signal that incorporated "director-type" information (COMMAND condition) more accurately than a FLOLS display that was augmented by "status"[5] information (RATE condition). Performance using a conventional FLOLS, which provided qualitative information about current position only, was inferior to the other two conditions. The differences, measured by RMS height, were statistically significant. Nine of the ten pilots who served as subjects preferred the director-type COMMAND display.

The same principle has also influenced the design of aircraft flight instruments and it is now common in avionics to incorporate "command" or "director-type" information (Warner 1979). Similarly, improvement in simulated flying accuracy is obtained. Niessen, Perry and Patton (1980) found that for those pilots who used instrument displays with vector information and without explicit command information during instrument approaches, a higher workload and a more variable flight trajectory resulted than for pilots who controlled a helicopter simulation with "command" instrument displays.

Cumming (1962) criticised Red-White VASIS because it lacks "director-type" information and because it gives inadequate information about current position in relation to an acceptable glidepath. T-VASIS, on the other hand, does include both "status" and "director-type" information. The advantages were apparent when pilots participated in a survey. A group of fifteen pilots naive to VASIs were asked whether the type of signal coding was "acceptable" or "instinctive". An analysis of the replies showed that 43% of the comments were favourable about Red-White VASIS coding whilst 100% were favourable about T-VASIS coding (Baxter, Cumming, Day and Lane 1960). Similarly, a survey of fourteen military pilots by Alexander (1962) found that the pilots often commented that the Red-White VASIS "on glideslope" signal required an amount of interpretation, whilst the same pilots commented favourably about the instinctive coding of T-VASIS.

PAPI provides information about current "status" (e.g. three red lights, one white light means "you are too low") but another step of interpretation is required before the pilot can decide to implement the appropriate response (e.g. "you are too low", "fly up"). Therefore PAPI lacks "director-type" information, as does Red-White VASIS.

Further, PAPI shares other features of Red-White VASIS signals which have been considered undesirable for easy interpretation, viz.:

(i) *"On-glideslope" signal*
The "on-glideslope" signals of both Red-White VASIS and PAPI require more interpretation than the same signal in T-VASIS. The T-VASIS "on-glideslope" signal tells the pilot that "all is well", with extra cues (i.e. the leg units forming the "T") appearing only if a deviation occurs.

(ii) *Gross undershoot signal*
The gross undershoot signal of both PAPI and Red-White VASIS are not separate and distinct warnings like the T-VASIS warning but, instead, are part of the normal set of signals.

(iii) *Use of red light as part of a normal signal*
Pilots have stated that the use of all red light in the "too low" Red-White VASIS signal is a favourable aspect (Alexander 1962) and presumably other pilots would agree that PAPI has the same favourable feature. However, the use of red light as part of the "on-glideslope" signal has not been recommended (Baxter and Lane 1960) because in aviation "red lights mean danger". T-VASIS does not suffer this disadvantage; signals are all white light until the red gross undershoot signal appears which signifies "danger".

Another difficulty with interpreting PAPI signals relates to the congruency between the direction of the display and the direction in which the pilot is required to correct the flight path.

[5] N.B. "Status" is used here with the same meaning used by Cumming (1962) after Calvert. "Status" encompasses information relating to both position and current trends.

The information about altitude changes provided by PAPI is orthogonal to the correction line. Several pilots have commented adversely about this incongruency (VAP 1980, para 1.4.31), and it could be expected that tracking accuracy would be improved if the display were compatible with the direction of control. In contrast, T-VASIS signals and Red-White VASIS signals (to some extent) are congruent with the required direction of control, although only T-VASIS specifically indicates the direction.

The various claims that PAPI is easy to interpret therefore require careful analysis, as there are a number of facets to the issue which have not been addressed previously. Surveys to date have not accounted for these subtleties when questioning pilots and, until further detailed information is obtained, the issue remains unresolved.

4.5.3 Frequency of viewing the signals

Tracking proficiency is also influenced by the number of times a person observes a signal and observing behaviour can be correlated with both the quantity of information and the rate at which the information changes (Lewis and Mertens 1979*a*). In their second experiment Lewis and Mertens (1979*a*) found that when pilots were allowed to view the simulated visual world, intermittently at their own discretion, the number of occasions selected was less for 3-BAR Red-White VASIS than for T-VASIS; late on approach about 30% fewer observations of Red-White VASIS were made.

They predicted that on some occasions especially during the later part of an approach using Red-White VASIS a pilot may fail to observe a critical signal. The example chosen to illustrate this prediction was a slightly steeper path than the nominal 3° where for most of the time the Red-White VASIS signalled "on-glideslope". They conjectured that a pilot continually seeing this signal from the VASI could be inclined to decrease his frequency of viewing and so fail to make an observation when or sufficiently soon after the "too low" signal appeared.

A possible example of this, earlier than the prediction, is an accident in which a DC-6B landed short of the runway at La Guardia Airport, New York, in 1962. This accident was noted some years ago by Milne from DoT and he kindly allowed his analysis to be reproduced here (Milne 1981). The pilot claimed that he saw a "red over white" indication showing that he was "on-glideslope" during the entire descent phase. Figure 7 shows that if the pilot had actually flown a stable but slightly steeper approach angle than the nominal 2°52′ set at La Guardia, he indeed would have seen an "on-glideslope" signal for most of the approach.

In a similar situation both T-VASIS and PAPI would provide frequent warnings to the pilot that the trajectory was unsatisfactory (see Figs 8 and 9) encouraging observation of the signals and correction to the flight path.

4.5.4 Corridors versus sectors: height versus angle

Both T-VASIS and Red-White VASIS define approach corridors. The geometry of T-VASIS allows the (seven) corridor widths, and hence the sensitivity of the information, to be adjusted as required and both ends of the approach can be optimised simultaneously. These features are not shared by Red-White VASIS because the sensitivity obtained close to the runway must be traded against the loss of effective visual range as the two bars are moved closer together. In addition, the wide transition zones emitted from standard slot-type boxes force the system's sensitivity to change with range.

The use of the "corridor" concept in both T-VASIS and Red-White VASIS avoids the guidance characteristics possessed by their respective predecessors—the PVG and the AAI (and its generic derivatives, the three-colour Glide Path Indicator, VAPI, and "Bardic" which is a device familiar to the Australian military). Although their geometry differs, the AAI and PVG effectively emit signals from a point source thereby producing sectors of information and giving guidance about angular deviations from the glidepath. These features (point source and angular feedback) were considered undesirable and thus avoided in later VASI designs. PAPI, with its sectors, returns to the concept of angular guidance.

One of the criticisms of the AAI related to its sensitivity. It was thought that the "on-glide-path" signal was too narrow at close range (Sparke 1958), but this sector was significantly larger at 2° (or 1° depending on the configuration—see Sparke 1958) than the sectors of PAPI which are proposed (10′, 20′ or 30′). The sensitivity of the PVG was also criticised (see Baxter, Cumming, Day and Lane 1960) mainly because the guidance at the beginning of the approach did not change sufficiently (i.e. it was too insensitive) when the guidance was effective close in. This poor feature of the PVG also stems from its geometry where, even though the signals are not actually produced from a point source, the effective guidance stems from a point.

The PVG provided guidance by requiring the pilot to discriminate whether two bars, set some distance apart along the runway side, were misaligned or not. The perceptual function involved in this judgement is known as vernier acuity which has surprisingly good thresholds of detection (Graham 1965). Following preliminary experiments (Cumming and Lane 1957*b*) it was shown by Baxter, Day and Lane (1960) that misalignments of about 39 seconds of arc offset in the image subtended at the observer's eye could be resolved in good conditions, and that pilots would choose to make an adjustment to their flight path when about 54 seconds offset occurred. These values were obtained at a range of 7 n miles and are comparable to the preliminary figures of Cumming and Lane (1957*b*) obtained at 3·5 n miles.

By extrapolation and interpolation, then, the minimum detectable misalignment could be considered as being equivalent to an angle of about one minute of arc offset over the majority of the PVG range (by ignoring perceptual movement thresholds and the effects on acuity of differences in the image size over range). As Sparke (1958) has pointed out, the sensitivity of the PVG information varies inversely with the square of the range, while the sensitivity of information from the standard Red-White *VASIS* varies inversely as a direct function of range (because the corridor sides are inclined at different angles). In comparison then, the PVG information becomes progressively more sensitive than Red-White VASIS as range decreases and the PVG shows a geometrical advantage close in. However, these geometrical differences are not reflected in the findings of field experiments (e.g. Baxter, Cumming, Day and Lane 1960). Pilots can approach with a similar accuracy regardless of whether the PVG or Red-White VASIS guidance is provided.

Because PAPI signals angular deviations, its information sensitivity also varies inversely with range. From past experience it could be expected that it may not be possible to optimise the sensitivity of PAPI for both ends of the approach. If the sectors are too wide, at long range the vertical distance between changes in the signals may be large enough to induce high descent rates to develop before the pilot receives further information; sectors which are too narrow at close range will almost certainly produce changes in the signals even on a relatively good stabilised approach.

A further criticism of angular systems was made by Sparke (1958) who believed that pilots need to know their displacement in height from, for judging their angle of descent relative to, the nominal glideslope. According to Sparke, this angle of descent can be deduced only from observing changes in linear displacement over time. A signalling system which indicates angular changes forces the pilot to first estimate his range before he can estimate his displacement, i.e. the pilot's "internal clock" would need adjusting with range. This idea of Sparke's has not received much subsequent attention from theorists. While pilots do use range dependent feedback, it is known that their tracking performance is subsequently improved if the signalling system is rate-aided and commanded (Lintern, Kaul and Collyer 1980). Neither type of assistance is provided by PAPI.

T-VASIS displays height deviation directly because the corridors are parallel or almost parallel-sided with only a small contribution from angle. This sensitivity was chosen to correspond closely with the ILS glidepath (Baxter, Cumming, Day and Lane 1960). It would be interesting to discover whether further improvement in tracking could be obtained by rate-aiding the height feedback.

4.6 Redundancy of Information

It is possible that occasionally a pilot may not be able to see or interpret every signal from a VASI. Leaving aside the catastrophic event where all or most boxes fail to operate, it is important that during normal operations there is enough redundant information in the signals for a

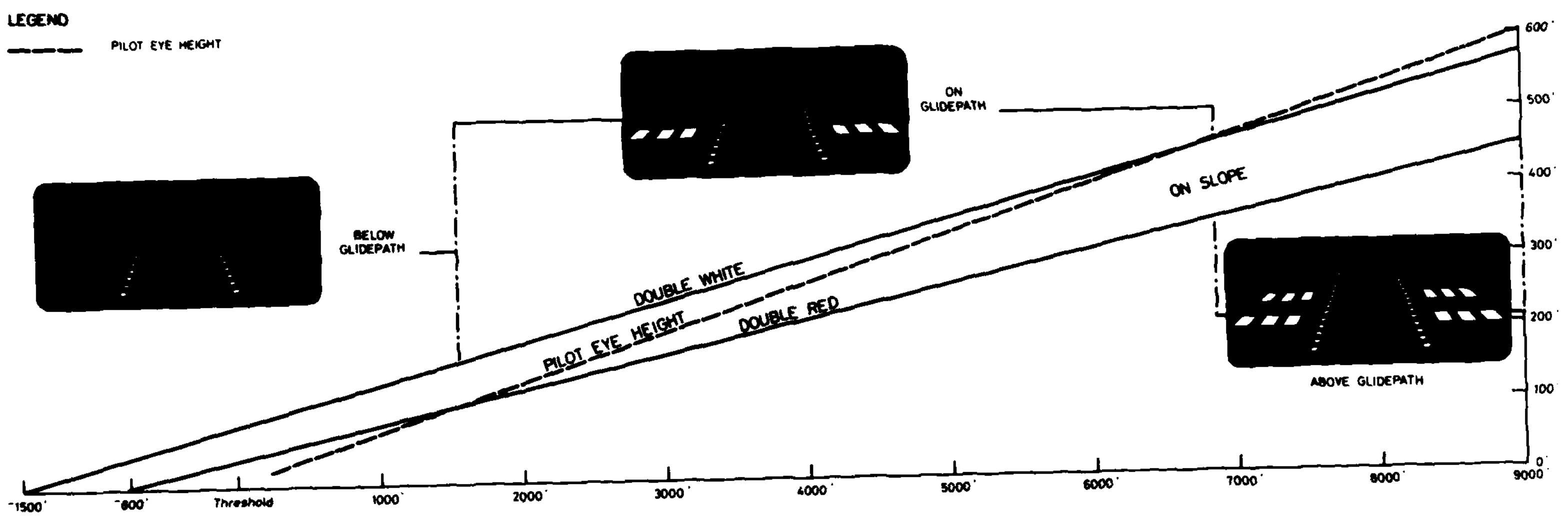


FIG. 7 HYPOTHETICAL STABLE TRAJECTORY SHOWING SIGNAL CHANGES IN RED-WHITE VASIS SEEN BY THE PILOT

(Note displaced aiming point as for the La Guardia accident)

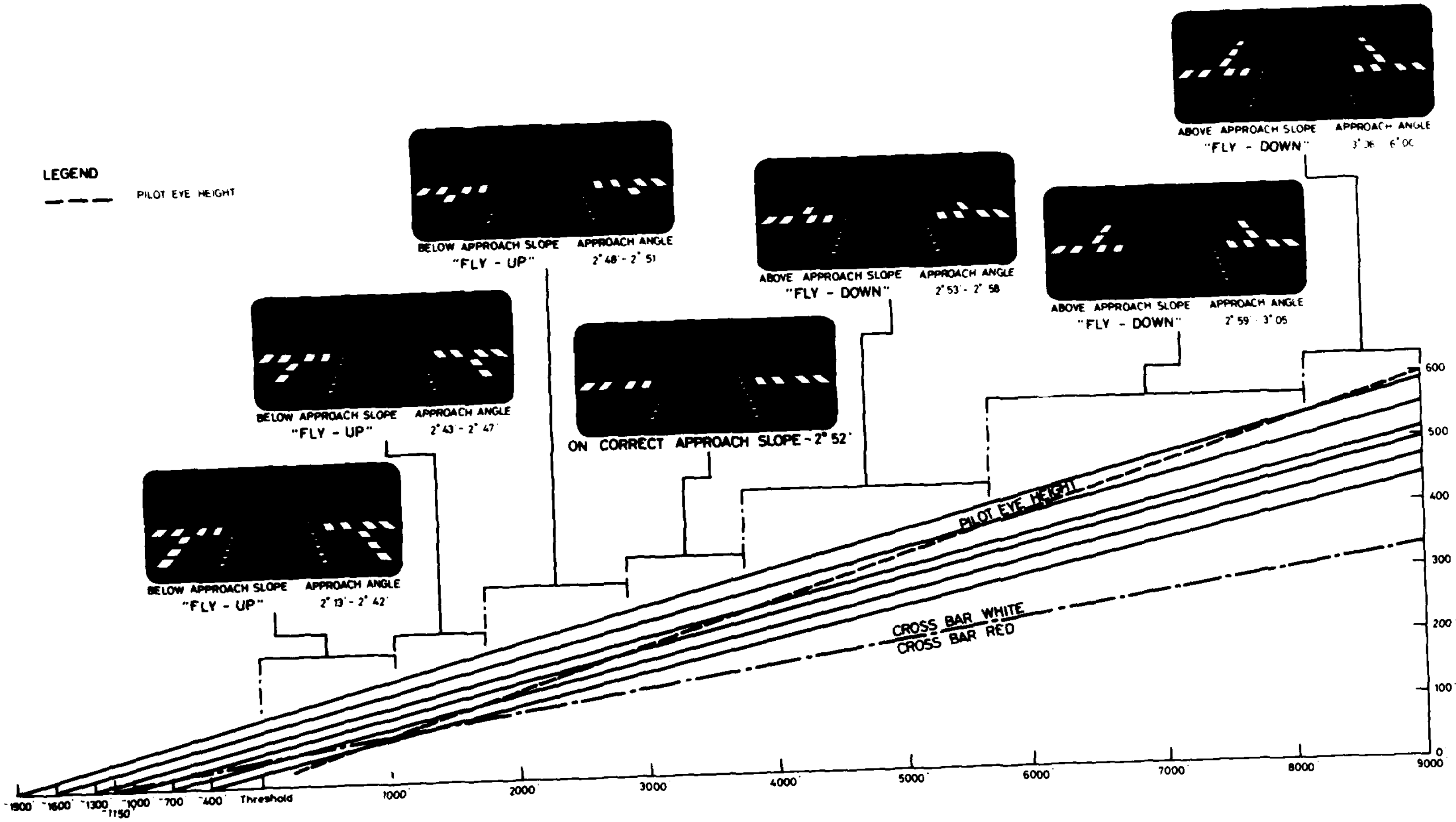


FIG. 8 HYPOTHETICAL STABLE TRAJECTORY SHOWING SIGNAL CHANGES IN T-VASIS SEEN BY THE PILOT

(Note displaced aiming point as for the La Guardia accident)

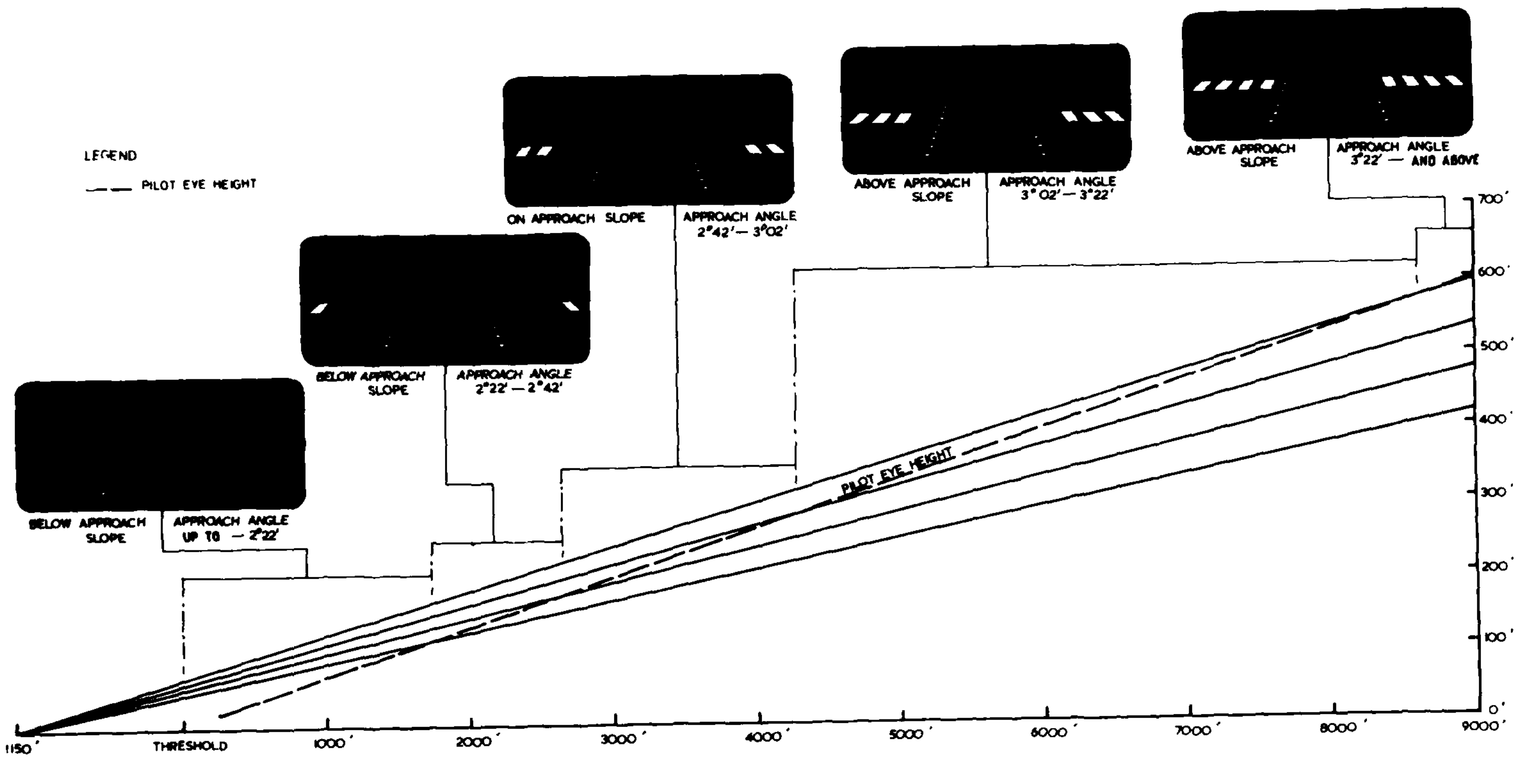


FIG. 9 HYPOTHETICAL STABLE TRAJECTORY SHOWING SIGNAL CHANGES IN PAPI SEEN BY THE PILOT

(Note displaced aiming point as for the La Guardia accident)

pilot to deduce where the aircraft is in relationship to the nominal glideslope.

During normal operations there are numerous occasions when the red signals of Red-White VASIS are not seen, but the white are, particularly when the pilot initially acquires the glideslope. The problem arises because the red light is generated from filtering the same source which produces the white, but at the expense of reducing the intensity of the red segment and therefore increasing the comparative visual ranges. (Matching the visual range of the colours can be achieved by neutral density filtering the white light as suggested by Smith and Johnson (1973), but this reduces the number of just noticeable differences between the signals (Clark and Gordon 1981).) The differences in the visual ranges of the colours in Red-White VASIS means that pilots will have difficulty in deducing their position, particularly in certain atmospheric conditions (see Section 4.2 above), and therefore they may not be able to attempt to establish a stable approach path early enough.

Similarly, PAPI signals also have ranges depending on their colour. In the laboratory experiments of Clark and Gordon (1981) the effective range of red signals generated by a commercial PAPI box was estimated to be about a quarter of that of the white. Photometric data from field experiments were unavailable to confirm this estimate. (The data of both Paries (1979) and Paprocki (1977) refer to modified Red-White VASIS slot-type boxes which have dimmer output and different coloured filters than manufactured PAPI boxes. Slot-type boxes will probably not be installed at operational airports—see Section 4.3 above.) However, Brown (1980) reported a range of 10 km (5·2 n miles) for the red signal, but Smith (1981) specified 1000 ft AGL (i.e. a range of about 6 km or 3 n miles on a 3° approach path).

When pilots are beyond the visual range of the red PAPI signals, Smith and Johnson (1976) suggested that the aircraft position may be derived by counting the number of white lights and inferring the number of red. This strategy would not, however, be failsafe. Clark and Gordon (1981) mentioned two ways in which a hazardous situation may arise in which pilots are not able to decide whether the (red) lights they see are red or white.

Because colour-coded VASIs are particularly vulnerable to misinterpretation, it is important that aids primarily relying on these codes contain supplementary information. For instance, the colours of Red-White VASIS are sometimes indistinguishable in certain viewing conditions (see Section 4.2 above) and the geometry of the box sites was designed in an attempt to alleviate this difficulty (Sparke 1958, Morrall 1960). It was thought that if the distance along the runway between the rows appeared to a pilot on a 3° approach to be equal to the width of a row, then glidepath departures would be noticeable when the ratio between these two lengths changed. Further reference to the efficacy of this cue was not found in the VASI literature reviewed here, but on the basis of field experiments dealing with the perception of other shapes (e.g. diamonds) for aircraft guidance, this cue could be, at best, considered to be a weak one, equivalent, perhaps, to the information obtainable from changes in runway perspective.

PAPI colours will undoubtedly be difficult to distinguish under some viewing conditions also, but redundant information using a different signalling code has not been provided. T-VASIS, by using colour coding purely as a secondary (redundant) signal, avoids these difficulties with the primary code.

VASIs also need redundancy in their signals in case equipment fails and one, or more, signals are not visible when they ought to be. Normally duplication of the VASI on both sides of the runway will reduce the hazards of equipment failure, but abbreviated systems are common enough to warrant consideration of the consequences here. For example, failure of individual lamps in a VASI box may occur, and will result in a reduced visual range of that box. This should not be of much significance for Red-White VASIS, because three boxes of lamps emit each signal and the bar effect will dominate. At night, two lamps operate in each T-VASIS box and failure of one will reduce the visual range, but even so, the range will still be well in excess of the ICAO-approved range. Paries (1979) mentions one possible failure of a lamp where PAPI signals could appear incorrect (i.e. a white light appears red), but this situation was not considered hazardous by him.

In the more unlikely event of an entire box failing or being occluded from view, one bar of Red-White VASIS will be less intense. For T-VASIS, even with a single sided system, no matter which box fails or is not seen (except for the uppermost leg box), there is enough redundant information for the pilot to deduce his position quickly. A failure of the last 'too low'

PAPI box (i.e. the box nearest the runway) could conceivably be dangerous because there is no ancillary information provided for the 'too low' condition.

The possibility of an entire set of leg units simultaneously failing in T-VASIS as suggested by Smith and Johnson (1976) is extremely remote and it is most likely that the wing bars would fail at the same time (Popple 1980). In this event, of course, the pilot would be aware that the entire system was not operating. Technical details about how the electrical circuits are designed to cope with this hypothetical problem fall beyond the scope of this paper.

4.7 Detection of Wind Shear

A matter receiving increasing attention at ICAO meetings has been the difficulty pilots experience in safely landing modern transport aircraft when wind shear is present. It could be reasonably expected that VASI signals which give quantitative information about position in relationship to a nominal glideslope over time, and therefore rate of change in position, would alert the pilot to the presence of shear.

Evidence about the usefulness of T-VASIS information in recognising when shear is present apparently derives from one survey of pilot opinion (Anderson and Clark 1981) and anecdotal accounts, and although opinions are useful as indicators of possible advantages, the practical effects remain to be verified objectively. However, two-thirds of all respondents in the Anderson and Clark survey marked the T-VASIS category, usually in conjunction with other cues. In the one simulator study found in the literature on operational aspects of approach and landing which included wind and wind shear, subjects apparently did not cite the simulated Red-White VASIS as a useful cue during any of the experimental runs (Stout and Stephens 1975).

PAPI was simulated in an experiment by Bisgood, Britton and Ratcliffe (1979) where wind shear was modelled during some runs and the subjects were asked to identify whether shear was present and to indicate the axes affected, also mentioning those cues which assisted them in making their decision. C· the specific cues mentioned (i.e. apart from the external visual scene which was quoted the most), PAPI and the airspeed indicator (ASI) were most frequently cited. However, pilots frequently claimed wind shear was present when it was not, claiming especially that vertical draughts existed, and according to the authors seemed to be basing these false identifications on the PAPI cue. On at least one-third of all occasions when vertical draughts were "recognised" on the basis of PAPI, the draughts were imaginary. Further, when PAPI was cited alone a statistically signficant number of the identifications were incorrect; in conjunction with another cue the assessments were more likely to be correct but the incidence of wrong judgements was still high (viz. about one-third).

These incorrect identifications attributed to PAPI may not be of much practical significance if pilots do not attempt to change their aircraft performance too much. However, the authors did not further analyse their data to assess whether the trajectories reflected these erroneous decisions, other than to say that generally landing performance was reliably better when no shear was present. Undoubtedly, as the authors conclude, PAPI is a useful cue for pilots to detect shear, but it is apparent from the simulation results that the reliability of judgements is improved if pilots use other sources of information as well.

5. DISCUSSION

It now seems generally accepted after many years of operational use that Red-White VASIS has a limited ability to assist pilots during an approach. Further, many operational requirements including compatibility with non-visual glidepaths, integrity of the signals in less than optimal meterological conditions, threshold clearance and maintenance aspects, have also been proven unsatisfactory. Many of these deficiencies, in particular the guidance characteristics, were convincingly demonstrated in experiments conducted prior to or at about the time that Red-White VASIS was accepted into the ICAO standards. In contrast, the earlier favourable experimental results with T-VASIS have been borne out during operational experience. It is

considered therefore that PAPI should be subjected to a rigorous experimental regime before it is routinely used.

However, as the review of PAPI reports has revealed (Section 3.4), much of the information collected was derived from pilot acceptance surveys. The early reports of operational trials in Britain where pilot opinion was collected showed a remarkably high approval for the system (Brown 1978, 1979) which was not maintained in later trials in the UK (VAP 1980, Appendix A), possibly indicating an influence from the "Hawthorne Effect". (This effect can result in the initial opinion that "anything new must be better than the old" but later, after experience with the system, opinions may reverse.) Pilot opinion also might have been unduly influenced by the style of the questions. These did not control for response bias or the "halo" effect (as previously mentioned in Section 3.4.1 above). The possible size of this effect could not be determined because the same style was used in all the trials reviewed here. Analysis of data was incomplete in many reports and statistical techniques were not employed to judge whether the response frequency in each category indicated a significant difference between the aids being compared. Further, the questions were not detailed enough to appraise specific PAPI characteristics properly, and important aspects remain to be assessed.

Insufficient performance data about PAPI (20′, 20′, 20′ and 20′, 30′, 20′) were available. In part, this lack of data may have stemmed from the development nature of PAPI when the aid was presented to ICAO for evaluation (VAP 1978). Several of the subsequent assessment efforts were devoted towards ascertaining suitable configurations for PAPI. For instance, Paries (1979) deliberately manipulated several design parameters such as the sector widths, the number of boxes installed in each row, the number of rows and the physical spacing between each PAPI box. In addition, a 2-BAR PAPI (since discarded) and the siting position along the runway of a one bar system was tested for wide-bodied aircraft in the Heathrow trials (VAP 1980), Castles (1981) assessed PAPI (20′, 30′, 20′), and a two box installation for light aircraft underwent investigation (FAA 1981). Other evaluations were preliminary and designed to test whether PAPI should be further investigated (e.g. Paprocki 1977; CAA 1977). The instructions to the PAPI Working Group to concentrate upon operational, technical and economic aspects may also gave diverted attention away from collecting performance data. However, despite the shortcomings of the various reports about PAPI, some useful conclusions and hypotheses may be drawn from theoretical grounds, in lieu of substantial experimental data.

In the late 1970s Brown (1978, 1979) when calling for a "second generation" VASI, echoed the sentiments of Cumming (1962) who said about Red-White VASIS:

> "Low precision guidance is inappropriate for current operations and will be quite unacceptable for the next generation of transport aircraft".

Cumming (1962) believed that the major differences in performance between Red-White VASIS and T-VASIS stemmed from the design philosophies underlying each aid. While T-VASIS allows the pilot to follow a precise approach when desired, Red-White VASIS only signals if tolerances have been exceeded, leaving the pilot unguided within the approach envelope. Consequently, the "bouncing" between the corridor limits is relatively common with Red-White VASIS and unstable approach paths with excessive rates of descent may sometimes develop.

The design philosophy of providing the pilot with more information about deviations from a satisfactory approach underlies T-VASIS, and *prima facie* a similar philosophy underpins PAPI. In effect the advantages claimed for PAPI (which stem from the design philosophy according to Brown (1979)) are substantially those demonstrated by T-VASIS (Paries 1979).

While, theoretically, PAPI provides more information than Red-White VASIS, the adequacy of the PAPI guidance as measured by the accuracy and stability of approach could not be determined from the literature. Although it is clear from various operational trials that PAPI has been judged as acceptable by many pilots, insufficient attention has been devoted to ascertaining whether the signals can be followed at least as accurately as those of either T-VASIS or Red-White VASIS. Of the available evidence only the experiments of Paries (1979) have perhaps established an advantage over Red-White VASIS for medium-weight aircraft,[6] but the PAPI configuration used in these trials was more sensitive than the two proposed as standards to ICAO.

[6] N.B. Further experiments using more pilots are required to establish this difference firmly.

There seem to be three strategies pilots might use on approach with PAPI. Possibly the approach with the least deviation implements a shallow scalloping strategy by tracking the mutual boundary between two sectors. This strategy is reflected in the graphs illustrated by Smith and Johnson (1976), but Ross (1980) has suggested that only skilled pilots familiar with their aircraft could use such a method successfully. Another possible strategy could arise of changes in PAPI signals were used to denote a divergence not to be exceeded. Paries (1979) reported that pilots in his experiment tended to regard PAPI signals in this way probably because of their prior experience with Red-White VASIS. If pilots used PAPI like this they would track within one sector and may "bounce" between the upper and lower boundaries. A third alternative is to use the PAPI signals as indicators of position, in a similar manner to many of the approaches recorded with T-VASIS where pilots close gradually onto the approach corridor. However, approaches with these characteristics were not observed in the published PAPI data, and it could be expected that deviations will be the greatest with this method because of the angular nature of the signals. Although high rates of descent could possibly develop at range with this method because the sectors are wide, it might be preferable to the two preceeding strategies which could have the (hypothesized) disadvantages of causing over-control or pilot-induced oscillations.

It remains to be determined which (if any) of these strategies will be adopted by the majority of pilots, and what the consequences on flight profiles and landing performance might be. Moreover, both the effects of prior experience with Red-White VASIS and the ability of pilots routinely using PAPI remain unexplored. Knowledge of these performance factors is important, not only for assessing the adequacy of PAPI guidance, but also for specification purposes. For instance, the choice of PAPI sites along the runway might be assisted if the proposed reduction in threshold clearances were supported by experimental data.

In other design aspects PAPI is quite different from T-VASIS. For instance, the ergonomics of the code could make PAPI less easy to interpret because, as outlined in Section 4.5.2 above, command information is absent, the signals are asymmetric and inconsistent with the required direction of control, the feedback displays angular deviations and red light is used as part of the normal signal. These aspects do not augur well for minimizing a pilot's reaction time to changes in PAPI signals. It has been well established that even test pilots who are prepared for an engine failure take 3 to 4 seconds after the first indication to apply the brakes when an engine fails on take-off; pilots who are not forwarned take even longer (4 to 5 seconds) (Foxworth and Marthinsen 1969). Research has shown that reaction time may be partitioned into a number of components. Zeller (1970) judged the components of a pilot's reaction time in a generalised decision task to be in the order of 0·03 to 0·3 of a second for the perceptual lag of a neural impulse to reach the brain from the eye, perception to take up to 0·5 of a second, decision time (which includes interpretation, integration and decision) to take up to 1 second, and several tenths of a second for a motor response to be initiated. Clearly, the easier the signal is to interpret the faster the pilot can respond.

Further, the primary signalling code of T-VASIS uses pattern perception while the design of PAPI repeats the undesirable colour-coding of Red-White VASIS. Clark and Gordon (1981) have outlined the fundamental objections to using colour coding in signalling systems and these disadvantages have not been overcome despite the narrower transition zone ridding PAPI (in theory) of much of the anomalous pink signal. To achieve the sharp transition, lens-type boxes (which fail "unsafe") are necessary. If lens-type boxes are endorsed for PAPI then perhaps Red-White VASIS would benefit from them also, and it would be interesting to compare the performance of the two systems following the suggestion of Lewis and Mertens (1979*a*) (see Appendix A).

In an effort to overcome the objections to colour coding, Smith (1981) has argued that the primary code of PAPI is borne by the white signals, but an equally, or even more, acceptable argument could be that the red lights bear the code. The latter argument is based upon the proposition that the red lights signal unacceptably dangerous low limits to an approach; a high indication is safer. In either case the difficulties with colour coding are not mastered.

Much of the impetus for developing PAPI as an aid for international transport aircraft seems to have stemmed from the proposition that all current and future [*sic*] aircraft landing operations could be satisfied (Smith and Johnson 1976). The essence of this proposal is attractive from a viewpoint of standardisation. However, the subsequent development of PAPI has revealed

that it has serious deficiencies, even beyond those shared with Red-White VASIS, in its ability to fulfil operational requirements for transport aircraft. For instance, angular point-source guidance is used, lens-type boxes seem mandatory, sometimes the ICAO-approved visual range may not be achieved, there is no redundancy in the signals and the proposal of a one sided system makes PAPI particularly susceptible to the hazards of equipment failure. Further, it seems that wide-bodied aircraft cannot be accommodated unless threshold clearances are lowered, or the nominal aiming point is moved upwind, degrading ILS compatibility, or a combination of both, and conventional aircraft will be disadvantaged by using such installations. The interpretation of Castle's (1981) data presented above (Section 4.1.2) suggested that the apparently superior features of PAPI approved by pilots may also be diluted by the current proposal for siting PAPI on runways used by both aircraft classes. Therefore, since superior performance has been demonstrated by T-VASIS, adapting this aid, rather than accepting a newer aid containing undesirable features of Red-White VASIS, may be more appropriate.

Preliminary development of T-VASIS to yield a less costly aid for secondary airports has begun (Gregson 1978; Leevers 1978*b*; Millar and Selway 1981). This modification, called RT-VASIS, uses only six boxes (instead of the usual ten or twenty). Flight trial testing of a modified T-VASIS similar to the RT-VASIS described by Gregson (but with different leg spacings and cut-off angles) has been independently assessed using pilot acceptance as the criterion in a formal experiment by Paprocki (1978). The approval expressed by the participating pilots supported the idea of modifying T-VASIS for use at secondary airports and Paprocki (1978) in his interim summary stated that the system "... would provide improved visual guidance to that offered by the present standard Red-White VASI system under all circumstances."

The Australian development of RT-VASIS was deferred (Pascoe 1980) when suggestions were made that RT-VASIS could replace T-VASIS. Both Baxter (1980) and the current author (Millar 1980) pointed out the deficiencies in RT-VASIS guidance for large transport aircraft. These include a reduction in the number of informational categories, decreased sensitivity in the feedback, unequal corridor widths (in one of the proposed configurations) and the absence of an extra "too high" category for wide-bodied aircraft. Paprocki (1978) also mentioned the last point. Nevertheless, if the sensitivity were formally tested and altered as appropriate for the intended class of aircraft, and if the use of RT-VASIS were confined as first suggested to minor airports, the system appears promising and further development could be worthwhile. Development of RT-VASIS for use on secondary airports would retain many of the advantages of T-VASIS and avoid the difficulties with colour-coded systems. The interests of standardisation would be achieved without introducing another (inferior) signalling concept.

6. CONCLUSIONS

The comparison of three Visual Approach Slope Indicators—VASIS, T-VASIS and PAPI—undertaken in this paper revealed major differences in the operational performance obtained between the aids or predicted from theoretical considerations. These differences were considered to stem mainly from the design philosophy on which the signalling systems were based and from the optical engineering of the hardware used to produce the signals.

T-VASIS was designed to provide precise guidance and may be used with varying accuracy as chosen by the pilot. The sensitivity has been optimised for transport aircraft and quick, reliable pilot response is ensured by using "director-type" pattern-coded signals. The standard system accommodates a wide variety of aircraft types by providing several approach paths close to 3° terminating at different points along the runway. Although it apparently has not been implemented, the sensitivity and approach angles of T-VASIS could be readily modified to suit other aircraft with different approach requirements (e.g. light aircraft, STOL aircraft) which land at secondary airports. T-VASIS signals have enough redundancy to be failsafe and are less susceptible to misinterpretation in adverse metereological and atmospheric viewing conditions than many other VASIs. The success of T-VASIS has been confirmed in numerous experimental evaluations and many years of operational experience.

In contrast, Red-White VASIS defines an approach corridor and only signals deviations beyond these limits. The information is therefore imprecise and pilots cannot accurately assess

their trends during an approach. Flight paths of transport aircraft using this aid are often highly variable and pilots also experience difficulty when judging their touchdown point because the feedback is inadequate and insensitive. The available evidence suggests that Red-White VASIS does not reduce the probability of a landing short accident from that of an unaided approach. Furthermore, it seems that one accident was not prevented by Red-White VASIS; instead the aid may have assisted the pilot to maintain an unsatisfactory approach.

The standard Red-White VASIS (using two bars) requires an extra bar to provide wide-bodied aircraft with adequate threshold clearance, but in doing so cannot maintain satisfactory compatibility between instrument and visual glidepath information. Various other configurations of Red-White VASIS have been developed and standardised for differing approach requirements, although their efficacy is debatable. The colour-coded signals of Red-White VASIS are particularly susceptible to alteration in atmospheric and viewing conditions which occur frequently and the signals perceived are also dependent upon the pilot's physiological state. The signals therefore do not fail safe. Furthermore, the visual range of the system frequently does not meet the ICAO standards.

Many of the installation and maintenance difficulties with Red-White VASIS could be overcome by installing sharp transition boxes using objective lenses but these are not recommended. Objective lenses exacerbate the hazards of colour-coding in VASI signals and do not fail safe. Accordingly, because of its overwhelming deficiencies, it is recommended that Red White VASIS not be used for routine operations in Australia.

The design philosophy of PAPI, which was developed from Red-White VASIS, attempts to provide the pilot with more information and superficially resembles that of T-VASIS. However, the success of the PAPI design could not be ascertained. The main emphasis of PAPI evaluations to date has been on pilot acceptance of the system. While a favourable response is undoubtedly a necessary prerequisite for any VASI being used operationally, information of this type is not very useful for assessing the adequacy of the guidance from PAPI. Objective measures of performance are a far superior method for assessment than subjective opinions, but only a minority of evaluations reported any parameters describing the flight paths obtained with PAPI. However, the reports containing parametric data were insufficiently detailed to enable the current author to evaluate the accuracy and stability of PAPI approaches.

In addition, some estimates of pilot acceptance were probably biased by the experimental method used when collecting the data. Although PAPI is preferred to Red-White VASIS by many pilots, detailed opinions about specific characteristics of PAPI and how pilots rated their performance were not collected. Accordingly, the performance of pilots using PAPI remains to be assessed, despite assertions to the contrary, and it is recommended that the aid be evaluated using objective measures in a controlled experimental environment with aircraft and pilots from the intended user population.

Consequently, in the absence of sufficient controlled experimental data, particularly parametric flight data, the comparison of PAPI with T-VASIS was mainly confined to theoretical and ergonomic principles. On the basis of these T-VASIS appears to be superior. PAPI perpetuates several deficiencies already experienced with Red-White VASIS including the absence of director or command information, the use of colour coding, unequal ranges of the two colours with the red signal unlikely to meet the ICAO-specified viewing distance, boxes constructed with objective lenses, and difficulties in maintaining compatibility between non-visual and visual glidepaths (although the incompatibility does not appear to be as severe as the difficulties with 3-BAR Red-White VASIS). PAPI does have advantages in comparison with Red-White VASIS (e.g. minimization of the transition zone, more categories of information, reputed ease when setting tolerances and maintaining them). However, PAPI returns to an older concept of VASI guidance by using convergent sectors in which the signals display feedback about angular deviations. In addition, the signals are asymmetric, emanate from sources placed perpendicular to the required direction of control and do not provide redundant information, particularly in one-sided systems. Therefore, because of its hypothesized ergonomic deficiencies, PAPI should not be installed in Australia for routine operational use at this stage. It is recommended that the development of RT-VASIS as a competitor to PAPI at secondary airports be reactivated.

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APPENDIX A

2-BAR PAPI

When PAPI was introduced into the literature by Smith and Johnson (1976), they suggested that a two bar configuration would accommodate wide-bodied aircraft, giving adequate threshold clearance and maintaining ILS compatibility. An approach corridor with diverging, parallel or convergent inner boundaries (depending on the incline of the sectors see Figure A1) can be defined by placing one row of PAPI boxes downwind of the ILS origin and the other upwind. This arrangement is similar to Red-White VASIS from which PAPI is said to derive (Brown 1979). Brown (1979, 1980; VAP 1978) subsequently introduced 2-BAR PAPI to ICAO as a possible contender for later inclusion in Annex 14.

Because two bars are used, there are nine signals available and consequently there are three ways a pilot of a wide-bodied aircraft could use to approach with 2-BAR PAPI so long as the inner corridor is not convergent. As shown in Figure A2, the pilot could approach using the upwind bar (Fig. A2*a*), the corridor between the two bars (Fig. A2*b*), or start the approach in the central corridor and transition to the upwind bar later in the approach (Fig. A2*c*). Similarly, a pilot of a conventionally sized aircraft could apply the same three techniques by using the downwind bar instead. If the corridor between the bars is convergent, then only one of the two bars could be used sensibly and the other would need to be ignored because the signals from each would be discrepant (Fig. A1).

The specified distance along the runway between the rows was suggested by Smith and Johnson (1976) as 120 metres (400 feet) for PAPI whilst usually 210 metres (700 feet) is specified by ICAO for Red-White VASIS. Smith and Johnson (1976) suggested a distance of 120 metres to ensure that discrepancies between the PAPI indications and the ILS signal were as small as practicable during most of the approach. The effect of the shorter distance between the PAPI rows is to narrow the approach corridor in the divergent or parallel configuration. Brown (1980) reported that when PAPI rows were installed at these distances apart, the signals from the two rows merged and became indistinguishable at about 6 km from the runway; a range less than the minimum visible recommended by ICAO. Presumably, this problem could be overcome by widening the gap between the PAPI bars but consequently a decrease in ILS compatibility is expected (VAP 1980, para 1.2.46). A similar solution was reached in the original design and testing stage of Red-White VASIS when the two bars merged at range (see Section 2.1 above).

The distance between the rows of 2-BAR PAPI was lengthened from that recommended by Smith and Johnson (1976) during developmental field trials by Paries (1979) and in the simulator experiment of Lewis and Mertens (1979*a*). Paries determined that the range where the signals could clearly be interpreted was 7 km when the PAPI rows were separated by 200 m (656 ft) and the boxes were spaced apart by 10 m. The visual range of Red-White VASIS with similar row spacing was 9 km. Paries explained that this difference in visual range was caused by the need to identify individual lights in the PAPI row conflicting with the 'bar' effect found in Red-White VASIS which helps to increase the visual range.

In a further set of development trials by Paries (1979), five approaches on average were flown to each of four 2-BAR PAPI configurations with varying sector sizes. The aim of these trials was to assess whether the work load involved for the pilot changed if the sector sizes were altered. The C172 aircraft used did not have ILS equipment onboard and so a technical observer orally tape recorded flight parameters (altitude, indicated airspeed, vertical speed, and inlet pressure) every 100 ft for comparison. However, Paries was unable to find a consistent correlation between narrowing the sectors and the mean values over trials, and he was unable to support objectively, the subjective reports that the narrowest two of the four configurations caused difficulties in piloting. In addition he reported that the standard deviation of most parameters decreased on

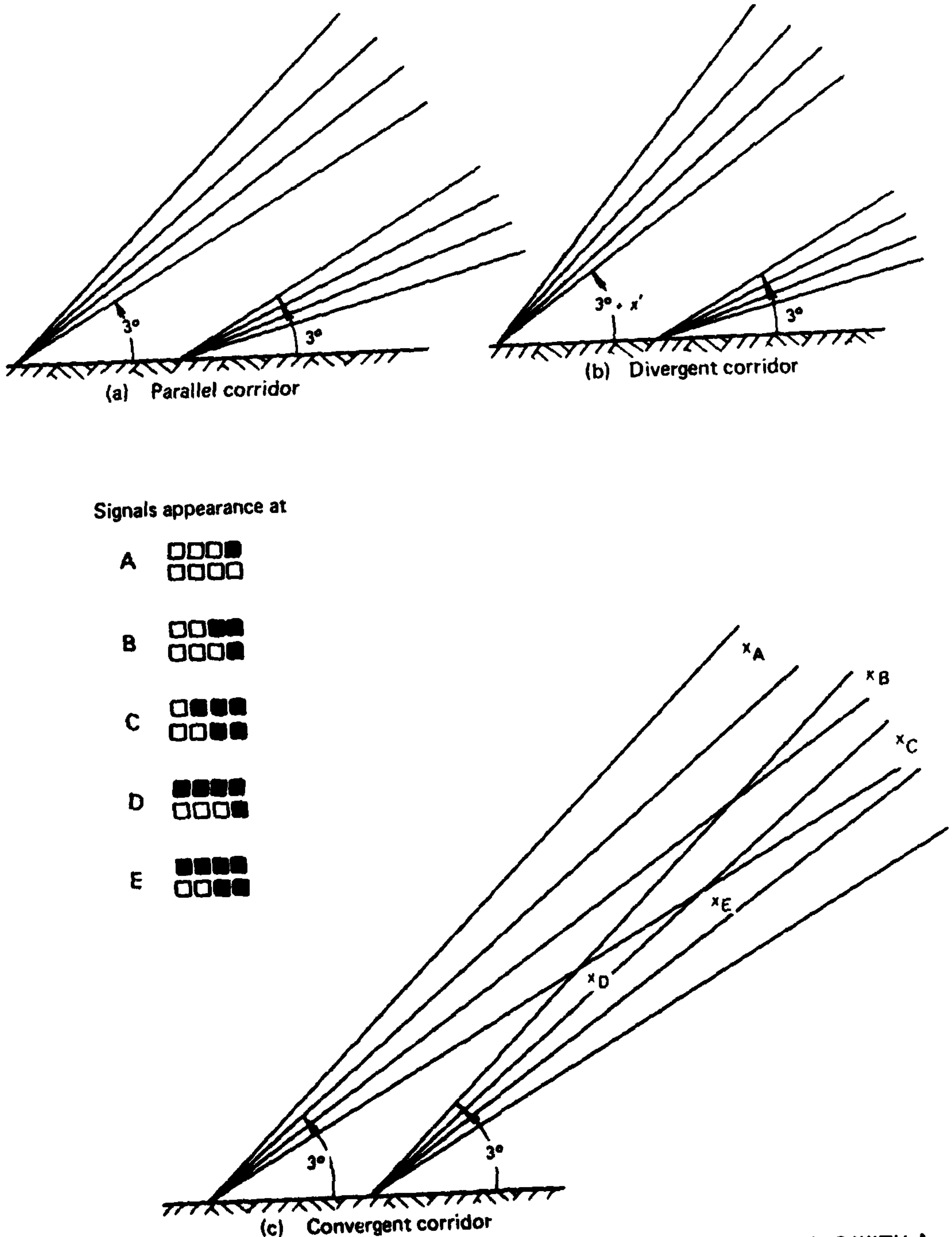

FIG. A1 METHODS OF ALIGNING 2-BAR PAPI SHOWING ANOMALOUS SIGNALS WITH A CONVERGENT CORRIDOR (not to scale)

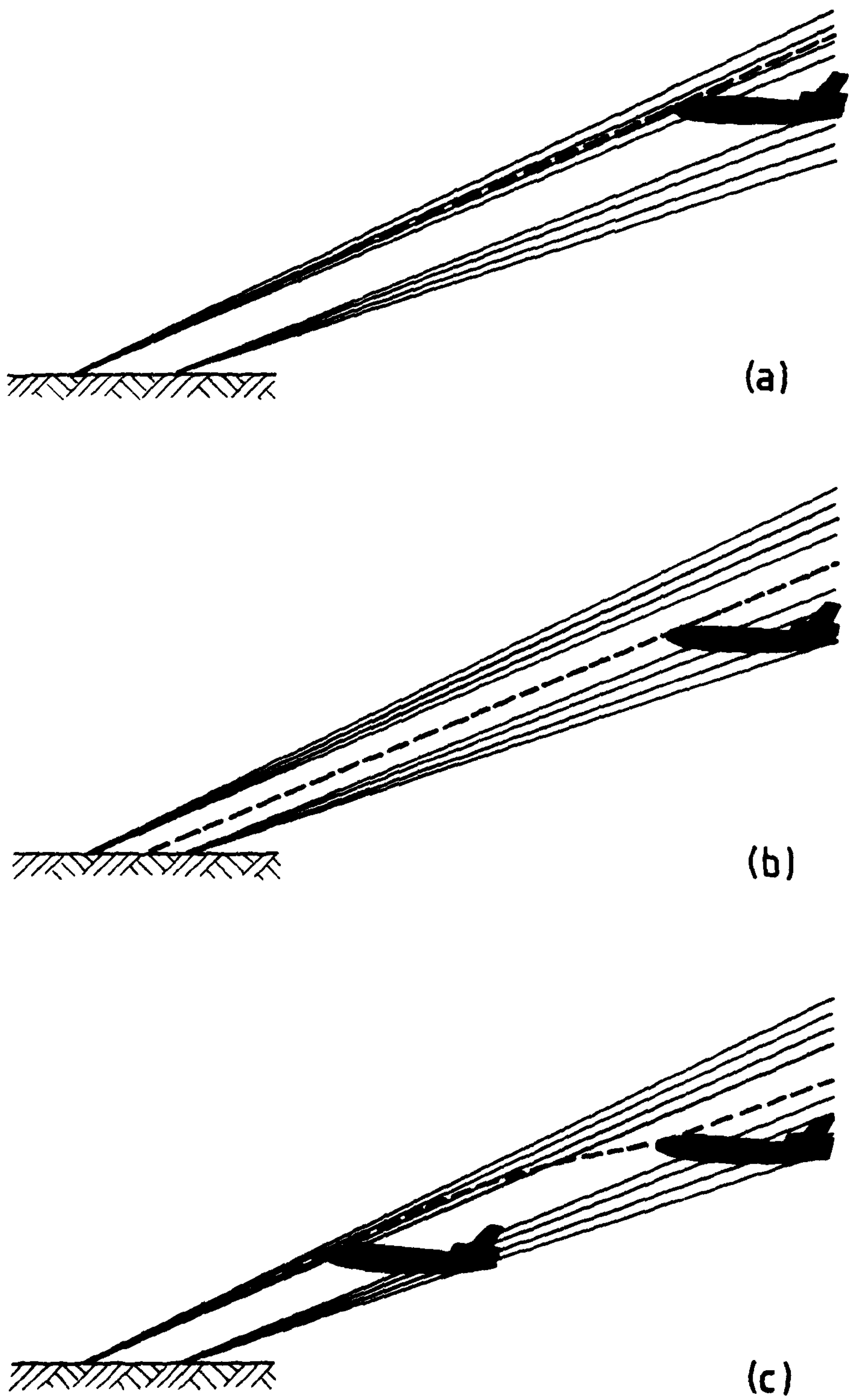

FIG. A2 THREE METHODS OF APPROACH WITH 2-BAR PAPI (not to scale)

successive approaches. Paries attributed this trend to the pilot's increasing familiarity with PAPI and the progression from wider to narrower sector sizes during the experiment.

The experiments of Lewis and Mertens (1979*a*) were designed to assess the ability of pilots to approach using various VASIs. (A shorter version of their paper was also published—see Lewis and Mertens (1979*b*).) Their study involved a comparison between four different VASIs: T-VASIS, 2-BAR and 3-BAR Red-White VASIS, and 2-BAR PAPI (20', 20', 20'). The bars in the last three VASIs were spaced apart by a simulated distance of 700 feet along the runway with the "on-glideslope" approach channel delineated by diverging light sectors set at 0·5°, 0·25° and 0·16° respectively. The simulation model was based upon a Convair 580 aircraft and night-time was depicted.

Lewis and Mertens could not distinguish statistically between the root mean square (RMS) deviation in height obtained over all trials between the VASIs tested in Experiment 1, but differences were obtained between T-VASIS and 2-BAR Red-White VASIS in Experiment 2 when only these two VASIs were tested. There was however, a consistent trend for deviations in height of the T-VASIS group to be smaller, both as range decreased and over trials in Experiment 1, than the equivalent deviations of height by the 3-BAR Red-White VASIS, 2-BAR PAPI and 2-BAR Red-White VASIS equivalent groups (in that order). Measures of angular deviation from glidepath (RMS generated approach angle—GAA) showed that the approach angle increased in size as distance to the runway decreased, but Lewis and Mertens again could not distinguish between the VASIs over all trials and, unsurprisingly, the GAA trends showed the same order of performance.

There were, however, learning (or practice) effects found in Experiment 1. The T-VASIS group pilots were significantly more accurate on the third (and final trial) than the 2-BAR Red-White VASIS pilots judging from RMS height parameters and on the second and third trials using RMS angular deviation. Pilots in the 3-BAR Red-White VASIS and 2-BAR PAPI flew with smaller angular deviations than 2-BAR Red-White VASIS pilots on the third trial. Lewis and Mertens (1979) did not specify whether these performance advantages were confined to particular ranges or whether they occurred at all ranges.

There were also differences between the pilots from each VASI group when they approached in the control "no VASI" condition. Pilots in the 2-BAR PAPI and 3-BAR Red-White VASIS groups deviated from a 3° approach slope less than pilots in the 2-BAR VASIS group which in turn could not be distinguished from the T-VASIS group. This bias may have stemmed either from the unequal experience of the pilots assigned to each group (see below) or may have been a consequence of training transfer between VASI and no VASI trials, or both. However, because the differences between the groups in the no VASI condition were opposite to the trends found with the VASIs, the conclusions drawn from Experiment 1 by Lewis and Mertens are supported and it could be further argued, at least qualitatively, that T-VASIS improved performance more than did the other three VASIs.

These performance differences between pilots in the control conditions may partly explain why the influence of T-VASIS, 3-BAR Red-White VASIS and PAPI on tracking accuracy could not be distinguished statistically in Experiment 1. Although the experiment was carefully designed to avoid possible asymmetric transfer effects which can confound performance (see Poulton 1974), the random assignment of subjects to groups undertaken by Lewis and Mertens may have been inadvertently unbalanced. It is useful to note that the T-VASIS group pilots had fewer flying hours experience (about 40,000 in total) than pilots from the other groups (from 45,500 to about 57,000) (see Table 1, in Lewis and Mertens (1979*a*)). The T-VASIS group also contained three pilots with fewer than 1000 hours, while only one such pilot participated in each of the other three groups. In unpublished experiments by Selway and the current author, pilots' ability to track simulated VASIs was related to their previous experience in hours and to the type of aircraft (pilots with helicopter experience being generally better under the conditions than commercial pilots or those with primarily military transport experience).

Regardless of the lack of significance between three of the VASIs, the results of Lewis and Mertens' study are particularly interesting because their findings conflict with the opinions and assertions commonly stated about PAPI. It could be expected from the representations to ICAO (e.g. VAP 1978; VAP 1980), aviation journal articles (see Section 3.4.1 above) and other reports (e.g. Smith and Johnson 1976) that PAPI would have ranked closer to T-VASIS than did 3-BAR Red-White VASIS. Lewis and Mertens (1979*a*), when discussing their findings,

could not account for this apparent anomaly because previous reports about PAPI did not provide enough data. They did speculate, however, that the major reason for the poor performance of 2-BAR Red-White VASIS may have been caused by the 0·5° incline between the rows and suggested that the system could be improved by decreasing this angle. (This could be achieved in practice by using sharper transition boxes.)

A 2-BAR PAPI installation was also operationally tested by collecting pilot opinion at Heathrow Airport. Several unfavourable comments were received including the merging of the bars at a distance, an excessive number of lights and the changing of signals in one bar when a pilot was following the other. Only one pilot commented upon this latter point, even though many others presumably saw the same phenomenon because the individual bars were set at the same angles (CAA 1979) and therefore defined a convergent corridor. As mentioned above, to avoid pilots seeing discrepant signals from the two bars the setting angles must be adjusted so that the inner corridor between them is parallel or divergent, not convergent. However, response percentages on all items were almost the same for the two bar system as for the one bar and 84% of pilots rated PAPI better overall than Red-White VASIS (VAP 1980, Appendix A). Despite these preferences and also the better theoretical ability for achieving glidepath harmonisation and threshold clearance, the Visual Aids Panel accepted that PAPI should have only one row (VAP 1980, para 1.4.28).

APPENDIX B

Information Available to Pilots Evaluating PAPI During Operational Trials in the United Kingdom

The following excerpts from the CAA information circulars were published during the period when operational trials asking pilots for their opinions about PAPI were being conducted. A questionnaire used in the surveys was appended to each circular.

"2. Trials at the Royal Aircraft Establishment, Bedford and at a number of RAF aerodromes, using a wide range of aircraft, have confirmed the ease of interpreting PAPI, and greater accuracy than VASIS has been demonstrated."

CAA (1977)

"5. The Authority wishes to thank all pilots who have commented on the Gatwick installation. Much valuable information was gathered from their reports, which showed considerable support for PAPI."

CAA (1979)

"The Authority is grateful to all those pilots who have completed PAPI questionnaires. These have provided information which forms an important part in the case for international acceptance of PAPI that is being pursued in ICAO."

CAA (1980)

"4. In addition to indicating the correct approach slope, trials so far conducted indicate that PAPI has the following advantages over VASIS:—

(a) It assists interception of the required visual approach slope and the timely corrections of any subsequent departure from the desired flight path . . . [PAPI] will give an indication of the rate at which the aircraft is establishing itself on the visual slope, or diverging from it. Such information leads to greater flight path precision and results in less scatter in both flight path and touchdown point. Reduced touchdown scatter is especially advantageous where landing distance is limiting.

(b) As range reduces, displacement accuracy increases because the individual PAPI beams converge, and the system has been found to be usable until the aircraft is over the threshold. This short-range accuracy, combined with good rate information, is of considerable value in conditions of low cloud or windshear.

(c) The positioning of the aid provides a visual indication of the aiming point for touchdown.

(d) The PAPI guidance can be fully harmonised with the ILS down to short range."

CAA (1977, Appendix A)
CAA (1979, Appendix A)
CAA (1980, Appendix A)

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16. Abstract

The three Visual Approach Slope Indicators (VASIs), [Red-White] VASIS, T-VASIS and PAPI, approved by the International Civil Aviation Organisation (ICAO) for use by turbojet aeroplanes are compared here. The discussion is based upon published performance data including approach path measurements and pilot opinion, ergonomics and the ability to fulfil operational requirements.

It is concluded from flight trial data and operational experience that T-VASIS is a more precise and sensitive aid than Red-White VASIS which has several deficiencies known for many years. The current policy of not using Red-White VASIS for routine operations in Australia is supported by the conclusions of this report.

It is predicted that PAPI also will be less satisfactory than T-VASIS. This prediction is based mainly on ergonomic principles. Performance data about PAPI is limited and consists mainly of relatively uninformative pilot acceptance surveys. Because insufficient objective para-

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16. Abstract (Contd) *meters describing trajectories of aircraft from the intended user-population have been published, most of the claims for PAPI superiority remain unsubstantiated.* *Accordingly, it is recommended that PAPI be evaluated using objective measures in a controlled experimental environment with transport aircraft. Further, because of its ergonomic deficiencies, PAPI should not be installed in Australia for routine operational use by turbojet aeroplanes at this stage.*		
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